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Improved production systems for common bean in south-central Uganda: I. Liddugavu soil, II. Limyufumyufu soil

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Improved production systems for common bean in south-central Uganda
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II. Limyufumyufu soil

by

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DEDICATION

I would like to dedicate my thesis to all of my friends, neighbors, and family back home. I'm very thankful for each and every one of you and I'm happy that you continue to reach out to me, even as I work away from home. It has been tough being away from the family farm for many years but your encouragement to continue my education is my motivation.

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NOMENCLATURE

2014B	2014 second rainy season
2015A	2015 first rainy season
ALS	Angular leaf spot
BCMV	bean common mosaic virus
EC	electrical conductivity
ECCE	effective calcium carbonate equivalent
ERLM	economic return to labor and management
CEC	cation exchange capacity
CEDO	Community Enterprises Development Organisation
CFS	Conventional Farmer System
CIAT	International Center for Tropical Agriculture
FANTA-2	Food and Nutrition Technical Assistance II Project
FAO	Food and Agriculture Organization
HIS	High Input System
ICP-OES	inductively coupled plasma optical emission spectrometry
IFS	Improved Farmer System
PHI	pod harvest index
SNF	symbiotic nitrogen fixation
TSP	triple superphosphate
UEPB	Uganda Export Promotion Board
UGX	Ugandan shilling

UNESCO	United Nations Educational, Scientific and Cultural Organization.
USAID	United State Agency for International Development
USDA, NRCS	U.S. Department of Agriculture, Natural Resources Conservation Service
VWC	volumetric water content
WAP	weeks after planting

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ABSTRACT

Common bean (*Phaseolus vulgaris* L.) is the most important source of dietary protein in Uganda but current grain yields are extremely low. Beans are produced on a variety of soils in south-central Uganda but the two most important soils for bean production are the highly weathered Limyufumyufu (Ferralsol) and the relatively fertile Liddugavu (Phaeozem) soils. These two soils vary in level of pH and fertility and therefore must be managed appropriately. Beans managed under conventional systems have a yield gap of about 75% due to poor agronomic practices, soil infertility, lack of seed from improved cultivars, moisture stress, weed competition, and damage caused by pests and diseases. The objective of this study was to compare the productivity and net profitability of four bean cultivars grown under three management systems on Limyufumyufu and Liddugavu soils in Masaka District, Uganda. The experiment was designed as a randomized complete block in a split-plot arrangement. Management system was the whole-plot factor and included the Conventional Farmer (CFS), Improved Farmer (IFS), and High Input systems (HIS). Management systems differed for seed fungicide treatment (no vs. yes), seeding density (10 vs. 20 seed m^{-2}), plant configuration (scatter vs. rows), fertilizer applications (P, K, Ca, Mg, Zn, and S), rhizobium inoculation (no vs. yes), pesticide applications (no vs. yes), and frequency and timing of weeding. Subplots were four bush type common bean cultivars that differed for resistance to foliar pathogens. Increasing management level, independent of rainy season, and planting bean cultivars tolerant to common bean diseases improved bean grain yield.

On the Limyufumyufu soil, there were only grain yield differences between cultivars in the 2015A season; NABE 14 had the greatest grain yield (772 kg ha^{-1}), 168% greater than NABE 15 (288 kg ha^{-1}). The HIS with NABE 14 (1274 kg ha^{-1}), the HIS with NABE 4 (1225 kg ha^{-1}), and the IFS with NABE 14 (1025 kg ha^{-1}) were the best management system × cultivar combinations for grain yield. The increased yields for these management system × cultivar combinations were likely due to the cultivars' greater host plant resistance to several bean diseases and tolerance to low soil fertility. The economic return to labor and management was only profitable for the CFS ($40 ha^{-1}), and no differences were observed between cultivars. Additionally, both rainy seasons resulted in a net loss.

On the Liddugavu soil, mean grain yield was greater in the HIS (1275 kg ha^{-1}) than in the IFS (818 kg ha^{-1}) and the CFS (593 kg ha^{-1}). Across management systems, disease resistant NABE 14 had greater grain yield (1212 kg ha^{-1}) than NABE 15 (668 kg ha^{-1}), K132 (803 kg ha^{-1}), and NABE 4 (899 kg ha^{-1}). The HIS with NABE 14 had the greatest grain yield (1772 kg ha^{-1}). The increase in yield for NABE 14 was likely due to its greater host plant resistance to several bean diseases including angular leaf spot, bean common mosaic virus, and root rots. The economic return to labor and management resulted in many net losses in the 2015A season, except when planting NABE 14. Over both seasons, the greatest management system × cultivar combination was the HIS with NABE 14 ($559 ha^{-1}).

All inputs and seed of bean cultivars used were obtained locally, except the rhizobia, suggesting that increased yields are obtainable by farmers under both soils, especially when utilizing NABE 14 under improved management practices with increased inputs. However, increased profits are only obtainable under the Liddugavu. The greater level of infertility and need for higher rates of nutrients for enhanced bean production on Limyufumyufu resulted in poor yields and poor economic returns to labor and management. The need for inputs was too great for Limyufumyufu and the value of bean was too low to recover the investment for all improved management system combinations.

CHAPTER 1. GENERAL INTRODUCTION

Introduction and Justification

The common bean (*Phaseolus vulgaris* L.) was first domesticated in the upland regions of Latin America more than 7000 years ago (Graham and Ranalli, 1997) and likely spread into Africa during the slave trade and European colonization in the sixteenth century (CIAT, 1989; Graham and Ranalli, 1997; Wortmann et al., 1998). Today, beans are the most important grain legumes in Uganda, producing 876,576 Mt of grain in 2014 (FAOSTAT, 2014) and ranking 9th for production of beans in the world in 2011 (Ronner and Giller, 2012). Beans are an important food source in Uganda and a major source of dietary protein (Ronner and Giller, 2012). Consumption exceeds 50 kg of beans person^{-1} year^{-1} in some regions of Uganda (Wortmann et al., 1998a); however, it is uncertain if current bean production can supply the growing demand because the current population in Uganda is greater than 35 million people and is increasing faster than the rate of bean production (Wortmann et al., 1998; Nabhan et al., 1999; Bekunda et al., 2002; Kilimo Trust, 2012; Ronner and Giller, 2012; Uganda Bureau of Statistics, 2014). There is great concern for the increased pressure and large demand for protein, which increases the importance of continued research on improved bean production practices that address the need for greater use of fertilizers to remedy the nutrient deficiencies in these soils (Bekunda et al., 2002). This research is especially important now due to land degradation and nutrient depletion as a result of continuous cultivation and low use of external inputs, which has led to a decrease in crop yields (Ronner and Giller, 2012). There are many constraints that limit bean production in Uganda which result in bean yields up to 80 percent less than the potential yields (Kimani et al., 2001). This project attempts to identify those limitations and develop improved bean production systems that alleviate those constraints and help close the yield gap.

Objectives and Organization

This thesis presents two papers that identify practical methods to alleviate constraints to common bean production on two soil types of Masaka District, Uganda. The objective was to compare the economic and yield related results of four bean cultivars grown under a conventional and two improved management systems in order to determine which cultivar and system combination is the most productive and economical for each of the two soil environments.

Hypotheses

Improved production systems will increase grain yields and profits on both soils as input levels and management practices increase, especially when utilizing newer bean cultivars tolerant to foliar fungal diseases.

References

Bekunda, M.A., Nkonya, E., Mugendi, D., Msaky, J.J., 2002. Soil fertility status, management, and research in East Africa. East Afr. J. Rural Dev. 20, 94–112.

CIAT (Centro Internacional de Agricultura Tropical), 1989. Bean Production Problems in the Tropics. 2nd ed. Schwartz, H.F. and Pastor-Corrales, M.A. (eds.). Cali, Columbia. 726 p.

FAOSTAT, 2014. Uganda 2014 dry bean production quantity. http://faostat3.fao.org/download/Q/QC/E, Electronic source, accessed on 27 January, 2016.

Graham, P.H., Ranalli, P., 1997. Common bean (*Phaseolus vulgaris* L.). F. Crop. Res. 53, 131–146.

Kilimo Trust, 2012. Development of Inclusive Markets in Agriculture and Trade (DIMAT): The Nature and Markets of Bean Value Chains in Uganda. http://www.undp.org/content/dam/uganda/docs/UNDP%20Uganda_PovRed%20-%20Beans%20Value%20Chain%20Report%202013.pdf, Electronic source, accessed on 17 December, 2015.

Kimani, P.M., Buruchara, R.A., Ampofo, K., Pyndji, M., Chirwa, R., Kirkby, R., 2001. Breeding beans for smallholder farmers in Eastern, Central, and South Africa: Constraints, achievement and potential. Pan-African Bean Research Network (PABRA) Millennium Workshop, 28 May-1 June, Arusha, Tanzania, CIAT, Kampala, pp. 11-28.

Nabhan, H., Mashali, A.M., Mermut, A.R., 1999. Integrated soil management for sustainable agriculture and food security in southern and east Africa, Integrated soil management for sustainable agriculture and food security. FAO. Rome.

Ronner, E., Giller, K., 2012. Background information on agronomy, farming systems and ongoing projects on grain legumes in Uganda, pp 1-34. https://www.n2africa.org/sites/n2africa.org/files/images/N2Africa_Characterization%20Uganda.pdf, Electronic source, accessed on 27 January 2016.

Uganda Bureau of Statistics, 2014. National Population and housing Census 2014. Provisional results, 1–65. http://www.ubos.org/onlinefiles/uploads/ubos/NPHC/NPHC%202014%20PROVISIONAL%20RESULTS%20REPORT.pdf, Electronic source, accessed on 17 December, 2015.

Wortmann, C.S., Kirkby, R.A., Eledu, C.A., Allen, D.J., 1998. Atlas of common bean (*Phaseolus vulgaris* L.) production in Africa. Centro Internacional de Agricultura Tropical, Cali, Colombia. 133 p. (CIAT publication; no. 297).

CHAPTER 2. LITERATURE REVIEW

Introduction

There are many constraints that limit common bean production in Uganda; however, the main constraints are poor agronomic practices, soil infertility, lack of seed from improved cultivars, moisture stress, weed competition, and damage caused by pests and diseases (CIAT, 1989; Kilimo Trust, 2012; Sinclair and Vadez, 2012; Sebuwufu et al., 2015). Many farmers are currently looking for improved management systems to increase bean yields; however, there has been very little research conducted on management systems that alleviate the above-mentioned constraints in south-central Uganda. The constraints to common bean production are complex and are frequently inter-linked and occur simultaneously, however, for simplicity these constraints are presented separately below.

Agronomic Practices

In Uganda, most fields under cultivation are managed based on their soil's crop production potential and different soils are managed in their own way to reduce costs and to ensure profitability (Nabhan et al., 1999). Beans in Uganda are preferentially planted on darker more fertile soils if available (Mazur et al., 2014); however, not all farmers have access to these soils and therefore plant beans on weathered and nutrient depleted acidic soils.

Beans are typically grown in low-input systems and are usually intercropped in combination with maize, cassava, yam, banana, coffee, and/or groundnuts (CIAT, 1989;

Graham and Ranalli, 1997; Kimani et al., 2001). Although growing multiple crops is important to minimize the risk of crop failure, it has been shown that bean yields are reduced by intercropping with another crop (Kimani et al., 2001; Maingi et al., 2001). Sole crop beans, on the other hand, are not as typical in Uganda but it has been shown to be a successful practice for increasing yield (Maingi et al., 2001). Sole crop beans in south-central Uganda are typically scatter-planted at a density of about 10 seeds m^{-2}, which utilizes the land inefficiently. It is important to use space efficiently because the average farm size in Uganda is only 2 to 4 hectares and the mean plot size for beans is only 0.3 hectares (Ronner and Giller, 2012). Scatter-planting consists of randomly digging shallow holes throughout a field with a hand hoe and dropping a seed in the hole before covering the seed with soil. This method could be improved to planting beans in rows at an increased optimum density of 20 seeds m^{-2} (Uganda Export Promotion Board, 2005), which agrees with the range of bean densities described by Graham and Ranalli (1997). This planting method and density is ideal because beans planted in rows are easier to manage for pests such as insects, diseases, and weeds. Planting in rows also allows P fertilizers to be banded in row with seed. Banding P is more efficient than broadcasting when soil sorption capacity for P is high, when soil P levels are very low, when the crop has a limited root system, and when various soil properties or climatic conditions limit root growth and P diffusion (Brady and Weil, 2007). It is beneficial to band P in soils that have a high fixation capacity to minimize soil contact and to minimize the potential for P fixation with Fe and Al oxides (Brady and Weil, 2007).

Soil Fertility

Soil health is a great concern in Africa and according to a 2014 Montpelier panel report, up to 65% of land in Africa is degraded and nutrient deficient (Glatzel et al., 2014). In eastern Africa, soil fertility has been declining at an alarming rate due to soil fertility mining (Nabhan et al., 1999). This puts crop production on an unsustainable path because a large proportion of these soils are highly weathered with low nutrient reserves and therefore limited capacity to supply nutrients (Bekunda et al., 2002). Land degradation and nutrient depletion is a result of the current system of removing crop residues, short fallow periods, continuous cultivation, and low use of external inputs, which are not sustainable and inadequate at meeting the needs of nutrient outflows (Bekunda et al., 2002; Ronner and Giller, 2012). Infertile soils are particularly problematic in the Lake Victoria Crescent (Ronner and Giller, 2012) and trials in this region have shown soil fertility to be one of the three most limiting factors to common bean production (CIAT, 1989). These soils have reached the last stages of weathering with limited nutrient replenishment. Due to the low nutrient content, low cation exchange capacity (CEC), low organic matter content (OM), low water holding capacity, and negligible mineral reserves these soils need a high-level of soil fertility management to obtain high agricultural production.

The CEC is an important component to determining a soil's production potential because it is a measurement of the total amount of exchangeable cations that can be held by the soil, which indicates the soil's nutrient status (Jones et al., 2013). The exchangeable cations are either basic cations (e.g. Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) or acid cations (e.g. H^{+} and Al^{3+}) and whichever type dominates, basic or acid cations, determines the soil pH and acidity levels (Jones et al., 2013). The pH of a soil relates to both the ability of a soil to supply nutrients and to its potential aluminum and manganese toxicity problems (Ngabonziza, 2014). Soil pH, a measure of soil acidity, controls many physical, chemical and biological processes and properties affecting soil fertility. This determines the suitability of a crop to grow in a particular soil. Like many plants, beans perform better in slightly acidic soil with a pH in the range of 5.8 to 6.5 (Lunze et al., 2012). When the pH is in this range minerals are more soluble, microorganisms are more active, and nutrient uptake improves.

In acidic soils it usually isn't the H-ion itself that confers the negative effects on plants, but an indirect effect caused by a deficiency of many nutrients such as N, P, K, S, Ca, Mg, and Mo, which become less available at a lower pH value (Döbereiner, 1966). Acid soils are more prominent in high rainfall environments due to the leaching of mobile base cations from the soil, resulting in increased levels of Al^{3+} and H^+ cations (Voortman et al., 2003; Jones et al., 2013). Aluminum immobilizes P and increases soil acidity and cation concentrations (Jones et al., 2013). Aluminum is abundant in soil minerals, so there is always a source of aluminum ions when the soil pH drops below 5.0-5.5. Below this range, Al^{3+} ions become significant on cation exchange sites and in solution. The Al ions in solution interfere with cell division, causing plant roots to be shorter and less branched than normal. Root damage interferes with the uptake of water and of calcium, magnesium, phosphorus, and perhaps other plant nutrients. About half of the bean production areas in Eastern Africa have recorded Al-toxicity (Wortmann et al., 1998a; Broughton et al., 2003).

Beans are typically produced on a median soil pH between 5.0 and 6.0, however, 23% of bean production in eastern Africa occurs on soil with a pH below or equal to 5.0 (Wortmann et al., 1998a). Some of these soils have a strong soil acidity which can cause soluble Al and Mn to become toxic, which negatively affects bean growth and development (Döbereiner, 1966; Bekunda et al., 2002). When manganese toxicity in an inoculated soil is an issue, research has shown that an application of lime can increase the total N in beans 339 percent, on average (Döbereiner, 1966). When manganese toxicity is absent, liming may not be needed because nitrogen fixation has been shown to be abundant in acidic soils (Döbereiner, 1966).

Lime and fertilizer additions can overcome specific nutrient deficiencies, but fertilizers are expensive investments in rural Uganda and most farmers use low levels or no fertilizer at all (Bekunda et al., 2002; Chianu et al., 2011; Lunze et al., 2012), contributing to further nutrient depletion of the soil. Nabhan et al. (1999) suggested high inputs of nutrients and calcareous amendments to maintain soil chemical fertility and pH. Fertilizing beans can increase root and shoot growth, providing access to soil moisture (Beebe et al., 2014) and nutrients. It is therefore important to be aware of crop nutrient needs, especially nitrogen, phosphorus, and potassium, which are commonly deficient in these soils (Bekunda et al., 2002; Margaret et al., 2014; Sinclair and Vadez, 2012; Wortmann et al., 1998).

Nitrogen is needed in large quantities because it is an important component of all proteins and nucleic acids necessary for new, functioning cells (Sinclair and Vadez, 2012). Although beans are generally considered to be poor N fixers due to poor soil conditions, the ineffective native soil rhizobia, and the selection of early flowering cultivars for a short growth season (Hardarson et al., 1993; Graham and Ranalli, 1997), inoculation with an appropriate *Rhizobium* spp. has been shown to increase grain yields in East Africa (Maingi et al., 2001). High levels of N fixation have been documented when the crop is not limited by other constraints (Giller et al., 1998; Giller and Amijee, 1998; Hardarson et al., 1993), and for that reason it is very important to address low soil pH with lime. Lime is used to increase the CEC of a soil, to neutralize Al, and to increase the supply of minerals (Ca, K, and Mg) that positively influence N-fixation by rhizobia (Lunze et al., 2012).

It is also important to address low soil P to prevent severely reducing symbiotic nitrogen fixation (SNF) or limiting root expansion (Graham and Ranalli, 1997; Beebe et al., 2014). Soil P is commonly the most limiting nutrient in Uganda and is the most frequently deficient nutrient in African soils with deficiency recorded in 65% of the bean producing areas of eastern Africa (Wortmann et al., 1998a; Ronner and Giller, 2012). Phosphorus has high fixation rates in tropical soils due to a high affinity to iron, aluminum, and organic matter (Jones et al., 2013). Phosphorus becomes unavailable to plants when it moves to a solid phase and forms insoluble compounds, also known as sorption, which is a predominant process in the soils of Uganda. Sorption of P can be alleviated by liming and frequent applications of phosphorus fertilizer (Jones et al., 2013). Low availability of P results in low biological N_2-fixation (Ronner and Giller, 2012); therefore, sufficient phosphorus is essential for stimulating N_2-fixation (Döbereiner, 1966).

Select rhizobium strains that have high nitrogen fixation rates and are tolerant to acidic soil complexes are imperative for effective inoculations (Döbereiner, 1966).

Inoculants are produced for common bean at Makerere University for a price of $0.75 per pack at 150 g in size. The inoculants are produced with semi-sterile peat as the carrier and the strains were obtained from CIAT 899, which is the standard strain used for common bean (Ronner and Giller, 2012). However, very few farmers are aware of the benefits of rhizobial inoculants (Silver and Nkwiine, 2007; Ronner and Giller, 2012) and therefore likely do not inoculate bean seed.

Adequate levels of K are also required for improved drought stress, protection against biotic stresses, optimal growth and productivity, and to replenish K as cropping intensifies and higher amounts of K are exported from the field (Mengel and Kirkby, 1980; Oosterhuis et al., 2014). Potassium is frequently removed in greater amounts from fields in Africa than North America because crop residues are typically removed from the field at harvest rather than left on the soil surface (Giller et al., 2009), further worsening K soil deficiency (Oosterhuis et al., 2014). Additionally, K addition increases the competitiveness of bean and therefore may be a component of integrated weed management systems in bean production (Ugen et al., 2002).

Pests and Diseases

Research in East Africa has shown diseases and insect pests to be two of the three most limiting factors to common bean production and one of the greatest challenges confronting farmers (CIAT, 1989; Broughton et al., 2003). The prevalence and importance of each pest and disease varies depending on the location, season, year, and cultivar (CIAT, 1989; Kimani et al., 2001). The main biotic constraints in eastern Africa were listed in order of importance by Kimani et al. (2001) as angular leaf spot (ALS)

(*Phaeiosariopsis griseola*), anthracnose (*Colletotrichum lindemuthianum*), bean stem maggot (BSM) (*Ophiomyia* spp.), bruchids (*Zabrotes subfasciatus* [Boheman] and *Acanthoscelides obtectus*), root rots (*Fusarium solani* f. sp. *phaseoli*), common bacterial blight (CBB) (*Xanthomonas campestris pv. phaseoli*), aphids, rust, and bean common mosaic virus (BCMV) (*Potyvirus* spp.).

Bean stem maggots are widespread and cause serious damage, especially for late-planted crops grown under unfavorable conditions (Kimani et al., 2001). Aphids are important to control because they vector diseases such as BCMV (Kimani et al., 2001), one of the five major widespread bean diseases (Broughton et al., 2003). Low yields are often caused by a combination of pests and additional bean pests include thrips, pod borers and plant-suckers (*Helicoverpa*, *Maruca*, and *Clavigralla*), foliage beetles (*Ootheca* spp.), whiteflies (*Bemisia tabacci*), and pollen and blister beetles (Kimani et al., 2001). Lastly, heavy post-harvest losses are also very common and are usually associated with bruchids, which consequently force farmers to sell their beans immediately after harvest when farm gate prices are at their lowest (Graham and Ranalli, 1997; Kimani et al., 2001). Many of the pests and diseases listed above were also documented as constraints to production in an annual report from the Legume Innovation Lab (2014), documenting strong negative effects of foliar disease on bean yield in south-central Uganda.

Improved Cultivars

One of the most important strategies for addressing declining soil fertility and improving grain yield has been the development and deployment of bean cultivars with improved tolerance to low nitrogen, low phosphorus, soil acidity (and accompanying manganese and aluminum toxicity), efficient utilization of soil nutrients, and commonly occurring diseases (Kimani et al., 2001; Sinclair and Vadez, 2012). Disease resistant cultivars of beans are important in developing countries located in the tropics and subtropics where disease pressure is greatest and there is limited access to affordable pesticides and clean seed (Graham and Ranalli, 1997). Most of the landrace cultivars grown are susceptible to various production constraints which prevents them from reaching their full yield potential (CIAT, 1989). Conventional bean yields are typically only 20 % to 30% of the genetic potential of improved cultivars (Wortmann et al., 1998a). Cultivars that are disease tolerant offer a form of protection to farmers who are less likely to be able to afford pesticides and clean seed (Graham and Ranalli, 1997).

Although some improved cultivars have a yield advantage compared to local cultivars, tradeoffs among cultivars exist and Ugandan farmers choose which cultivars to grow based on soil fertility conditions, tolerance or resistance to heavy rainfall or drought, early maturity, quick cooking, taste, market prices, marketability, and productivity (Kilimo Trust, 2012; Mazur et al., 2012). Some cultivars that have a high potential for grain yield also have a major disadvantage such as requiring a longer cooking time and therefore more fuel for meal preparation (Mazur et al., 2012). Conversely, some lower producing cultivars require shorter cooking times, a preferred trait in Uganda (Graham and Ranalli, 1997; Mazur et al., 2012). It is also important to note that some lower yielding cultivars bring a higher market price.

There is a need for beans that will perform well under low soil fertility conditions under low input systems typical of smallholder African farmers. Using tolerant lines to different stresses including tolerance to low K, low P, low N, Mn toxicity, and Al toxicity have been developed and adopted by farmers (Lunze et al., 2012; Kimani et al., 2010). Improved cultivars not only protect against pests and diseases, they also protect the producer's profit margins (Broughton et al., 2003), which is important for farmers who are unable to afford pesticides and clean seed (Graham and Ranalli, 1997).

Economics

Many smallholder farmers realize the value of mineral fertilizers on their farm but the rate of application needed to improve crop production is usually great and the cost has not been affordable, which has led to very low application rates (Lunze et al., 2012). Nabhan et al. (1999) mentioned that a heavy application of fertilizer can be profitable on soils that have a high productive potential but which are low in fertility, which is descriptive of the Liddugavu soil in south-central Uganda. However, the profitability of soils with a low productive potential, such as Limyufumyufu (Ferralsol), has had very little bean research that included an economic analysis.

References

Beebe, S., Rao, I., Devi, M., Polania, J., 2014. Common beans, biodiversity, and multiple stress: challenges of drought resistance in tropical soils. Crop Pasture Sci. 65, 667-675.

Bekunda, M.A., Nkonya, E., Mugendi, D., Msaky, J.J., 2002. Soil fertility status, management, and research in East Africa. East Afr. J. Rural Dev. 20, 94–112.

Brady, N.C., Weil, R.R., 2007. The colloidal fraction: seat of soil chemical and physical activity, in: The Nature and Properties of Soils, 14th ed. Prentice Hall, pp. 310–357.

Broughton, W.J., Hernández, G., Blair, M., Beebe, S., Gepts, P., Vanderleyden, J., 2003. Beans (*Phaseolus* spp.) – model food legumes. Plant Soil 252, 55–128.

Chianu, J.N., Chianu, J.N., Mairura, F., 2011. Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agron. Sustain. Dev. 32, 545–566.

CIAT (Centro Internacional de Agricultura Tropical), 1989. Bean Production Problems in the Tropics. 2nd ed. Schwartz, H.F. and Pastor-Corrales, M.A. (eds.). Cali, Columbia. 726 p.

Döbereiner, J., 1966. Manganese toxicity effects on nodulation and nitrogen fixation of beans (*Phaseolus vulgaris* L.), in acid soils. Plant Soil 24, 153–166.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Res. 114, 23–34.

Giller, K.E., Amijee, F., 1998. Environmental constraints to nodulation and nitrogen fixation of *Phaseolus vulgaris* L. in Tanzania. I. A survey of soil fertility, root nodulation and multi-locational responses to rhizobium inoculation. Afr. Crop Sci. J. 6, 159–169.

Giller, K.E., Amijee, F., Brodrick, S.J., Edje, O.T., 1998. Environmental constraints to nodulation and nitrogen fixation of *Phaseolus vulgaris* L. in Tanzania. II. Response to N and P fertilizers and inoculation with rhizobium. Afr. Crop Sci. J. 6, 171–178.

Glatzel, K., Conway, G., Alpert, E., Brittain, S., 2014. No ordinary matter: Conserving, restoring and enhancing Africa's soils. Agriculture for Impact, pp. 1–40.

Graham, P.H., Ranalli, P., 1997. Common bean (*Phaseolus vulgaris* L.). F. Crop. Res. 53, 131–146.

Hardarson, G., Bliss, F.A., Cigales-Rivero, M.R., Henson, R. A., Kipe-Nolt, J.A., Longeri, L., Manrique, A., Peña-Cabriales, J.J., Pereira, P.A.A., Sanabria, C.A., Tsai, S.M., 1993. Genotypic variation in biological nitrogen fixation by common bean. Plant Soil 152, 59–70.

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M., Zougmoré R., (eds.), 2013. Soil Atlas of Africa. European Commission, Publications Office of the European Union, Luxembourg. 176 pp.

Kilimo Trust, 2012. Development of Inclusive Markets in Agriculture and Trade (DIMAT): The Nature and Markets of Bean Value Chains in Uganda. http://www.undp.org/content/dam/uganda/docs/UNDP%20Uganda_PovRed%20-%20Beans%20Value%20Chain%20Report%202013.pdf, Electronic source, accessed on 17 December, 2015.

Kimani, P.M., Buruchara, R.A., Ampofo, K., Pyndji, M., Chirwa, R., Kirkby, R., 2001. Breeding beans for smallholder farmers in Eastern, Central, and South Africa: Constraints, achievement and potential. Pan-African Bean Research Network (PABRA) Millennium Workshop, 28 May-1 June, Arusha, Tanzania, CIAT, Kampala, pp. 11-28.

Lunze, L., Abang, M., Buruchara, R., Ugen, M.A., Nabahungu, N.L., Rachier, G.O., Ngongo, M., Rao, I. 2012. Integrated Soil Fertility Management in Bean-Based Cropping Systems of Eastern, Central and Southern Africa, in: Whalen, J.K. (Ed.), Soil Fertility Improvement and Integrated Nutrient Management – A Global Perspective. InTech, pp. 239–272.

Maingi, J.M., Shisanya, C.A., Gitonga, N.M., 2001. Nitrogen fixation by common bean (*Phaseolus vulgaris* L.) in pure and mixed stands in semi-arid south-east Kenya. Eur. J. Agron. 14, 1–12.

Margaret, N., Tenywa, J.S., Otabbong, E., Mubiru, D.N., Ali, T., 2014. Development of common bean (*Phaseolus vulgaris* L.) production under low soil phosphorus and drought in Sub-Saharan Africa: A Review. J. Sustain. Dev. 7, 128–139.

Mazur, R., Tenywa, M., Sseguya, H., Semalulu, O., Maria, R., Sumila, C., Salégua, V., Abbott, E., Lenssen, A., Luvaga, E., Yost, R., Bello-Bravo, J., Pittendrigh, B., 2014. Farmer Decision Making Strategies for Improved Soil Fertility Management in Maize – Bean Production System, in: Legume Innovation Lab 2014 Annual Technical Progress Report. http://legumelab.msu.edu/project/s02_1_isu, Electronic source, accessed on 11 February, 2016.

Mazur, R., Nakimbugwe, D., Musoke, H., Vasanthakaalam, H., Kibwika, P., Bwambale, N., Westgate, M., Reddy, M., Ugen, M., Elepu, G., Jensen, H., Henrich, S., Murphy, P. 2012. Enhancing Nutritional Value and Marketability of Beans through Research and Strengthening Key Value Chain Stakeholders in Uganda and Rwanda, in: Dry Grain Pulses Collaborative Research Support Program, FY

2012 Technical Progress Reports, East Lansing, Michigan, pp. 3-40. http://legumelab.msu.edu/uploads/files/TechProgReportF12Final.pdf, Electronic source, accessed on 11 February, 2016

Mengel, K., Kirkby, E.A., 1980. Potassium in Crop Production. Adv. Agron. 33, 59–110.

Nabhan, H., Mashali, A.M., Mermut, A.R., 1999. Integrated soil management for sustainable agriculture and food security in southern and east Africa, Integrated soil management for sustainable agriculture and food security. FAO. Rome.

Ngabonziza, J.D., 2014. Effectiveness of native rhizobia isolates on productivity of climbing beans on limed acidic soil of Rwanda. (Master's thesis), Makerere University, Kampala, Uganda.

Oosterhuis, D.M., Loka, D.A., Kawakami, E.M., Pettigrew, W.T., 2014. The physiology of potassium in crop production. Adv. Agron. 126, 203-333.

Ronner, E., Giller, K., 2012. Background information on agronomy, farming systems and ongoing projects on grain legumes in Uganda, pp 1-34. https://www.n2africa.org/sites/n2africa.org/files/images/N2Africa_Characterization%20Uganda.pdf. Electronic source, accessed on 27 January 2016.

Sebuwufu, G., Mazur, R., Ugen, M., Westgate, M., 2015. Using improved varieties and fertility enhancements for increasing yield of common beans (*Phaseolus vulgaris* L.) grown by small-landholder farmers in Uganda. Afr. J. Agric. Res. 10, 4795-4805.

Silver, R., Nkwiine, C., 2007. A review of work on rhizosphere microbiota in Uganda. Afr. J. of Ecol. 45 (Suppl. 2), 20–26.

Sinclair, T.R., Vadez, V., 2012. The future of grain legumes in cropping systems. Crop Pasture Sci. 63, 501–512.

Uganda Export Promotion Board, 2005. Dry Beans: Product Profile No. 12. http://s3.amazonaws.com/zanran_storage/www.ugandaexportsonline.com/ContentPages/2470693312.pdf, Electronic source, accessed on 17 December, 2015.

Ugen, M.A., Wien, H.C., Wortmann, C.S., 2002. Dry bean competitiveness with annual weeds as affected by soil nutrient availability. Weed Sci. 50, 530–535.

Voortman, R.L., Sonneveld, B.G.J.S., Keyzer, M.A., 2003. African land ecology: Opportunities and constraints for agricultural development. AMBIO: A Journal of the Human Environment, 32, 367-373

Wortmann, C.S., Kirkby, R.A., Eledu, C.A., Allen, D.J., 1998. Atlas of common bean (*Phaseolus vulgaris* L.) production in Africa. International Center for Tropical Agriculture, Cali, Colombia. 133 p. (CIAT publication; no. 297).

CHAPTER 3. IMPROVED PRODUCTION SYSTEMS FOR COMMON BEAN IN SOUTH-CENTRAL UGANDA. I. LIDDUGAVU SOIL

A paper formatted for Field Crops Research

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Abstract

Common bean (*Phaseolus vulgaris* L.) is the most important grain legume in Uganda. Beans managed under conventional systems have a yield gap of about 75% due to poor agronomic practices, soil infertility, lack of seed from improved cultivars, moisture stress, weed competition, and damage caused by pests and diseases. The objective of this study was to compare the productivity and net profitability of four bean cultivars grown under three management systems on Liddugavu soil (Phaeozem) in Masaka District, Uganda. The experiment was designed as a randomized incomplete block in a split-plot arrangement. Management system was the whole-plot factor and included the Conventional Farmer (CFS), Improved Farmer (IFS), and High Input systems (HIS). Management systems differed for seed fungicide treatment (no vs. yes), seeding density (10 vs. 20 seed m^{-2}), plant configuration (scatter vs. rows), fertilizer applications (P, K, Ca, and Mg), rhizobium inoculation (no vs. yes), pesticide applications (no vs. yes), and frequency and timing of weeding. Subplots were four bush type common bean cultivars that differed for resistance to foliar pathogens. Increasing management level, independent of rainy season, and planting bean cultivars tolerant to common bean diseases improved bean grain yield. Mean grain yield was greater in the HIS (1275 kg ha^{-1}) than the IFS (818 kg ha^{-1}) and the CFS (593 kg ha^{-1}). Across management systems, disease resistant NABE 14 had greater grain yield (1212 kg ha^{-1}) than NABE 15 (668 kg ha^{-1}), K132 (803 kg ha^{-1}), and NABE 4 (899 kg ha^{-1}). The HIS with NABE 14 had the greatest grain yield (1772 kg ha^{-1}). The increase in yield for NABE 14 was likely due to its greater host plant resistance to several bean diseases including angular leaf spot, bean common mosaic virus, and root rots. The economic return to labor and management, over both seasons, was greatest for the HIS with NABE 14 (\$559 ha^{-1}). Many management system × cultivar combinations resulted in a net loss in the 2015A season, except with NABE 14. All inputs and seed of bean cultivars used were obtained locally, except the rhizobia, suggesting that increased yields and profitability are obtainable by farmers, especially when utilizing NABE 14 under improved management practices with increased inputs.

Keywords

Food security; *Phaseolus vulgaris* L.; soil fertility; management systems; improved cultivars; sustainable intensification

Acronyms and Abbreviations

2014B – 2014 second rainy season

2015A – 2015 first rainy season

ALS – Angular leaf spot

BCMV – bean common mosaic virus

EC – electrical conductivity

ECCE – effective calcium carbonate equivalent

ERLM – economic return to labor and management

CEC – cation exchange capacity

CEDO – Community Enterprises Development Organisation

CFS – Conventional Farmer System

CIAT – International Center for Tropical Agriculture

FANTA-2 – Food and Nutrition Technical Assistance II Project

FAO – Food and Agriculture Organization

HIS – High Input System

ICP-OES – inductively coupled plasma optical emission spectrometry

IFS – Improved Farmer System

PHI – pod harvest index

SNF – symbiotic nitrogen fixation

UEPB – Uganda Export Promotion Board

UGX – Ugandan shilling

UNESCO – United Nations Educational, Scientific and Cultural Organization.

USAID – United State Agency for International Development

USDA, NRCS – U.S. Department of Agriculture, Natural Resources Conservation Service

VWC – volumetric water content

WAP – weeks after planting

1. Introduction

Common bean (*Phaseolus vulgaris* L.) is the most important grain legume in Uganda (Beebe et al., 2014) and is produced primarily by smallholder farmers (Ugen et al., 2002). Per capita consumption in Uganda exceeded 50 kg year^{-1} in some regions about two decades ago (Wortmann et al., 1998a), but more recent countrywide consumption averages about 11-16 kg person^{-1} year^{-1} (Broughton et al., 2003). Although the per capita consumption has decreased, the total demand is still increasing due to population growth (Kilimo Trust, 2012).

Common bean is an important crop in Uganda because it is a common source of calories and a major source of dietary protein (Broughton et al., 2003; Graham and Ranalli, 1997; Mazur et al., 2012) that often substitutes for meat and other protein-rich animal products, which the poor can rarely afford (Kilimo Trust, 2012; Sinclair and Vadez, 2012; Amongi et al., 2014). The south-central region of Uganda experiences high rates of malnourished and micronutrient deficient children, especially for vitamin A and iron (FANTA-2, 2010; UBOS and ICF International Inc., 2012). Iron deficiency anemia (hemoglobin <11.0 g dL^{-1}) is as high as 80% in south-central Uganda (FAO, 2010). These nutritionally challenged diets can be overcome by increased consumption of beans, which will provide children with sufficient iron, protein, and micronutrients essential for their growth and development (Broughton et al., 2003; Kilimo Trust, 2012; Margaret et al., 2014; Mazur et al., 2012). Unfortunately, bean yield in south-central Uganda is low, further exacerbating these problems.

Beans managed under conventional systems are only producing between 500 kg ha^{-1} to 800 kg ha^{-1}, on average, despite having a potential yield of up to 2500 kg ha^{-1} (Graham and Ranalli, 1997; Bekunda et al., 2002; Broughton et al., 2003; Kilimo Trust, 2012). Bean production in Uganda is low due to numerous constraints including poor agronomic practices, soil infertility, lack of seed from improved cultivars, moisture stress, weed competition, and damage caused by pests and diseases (CIAT, 1989; Kilimo Trust, 2012; Sebuwufu et al., 2015; Sinclair and Vadez, 2012). Many farmers are currently looking for improved management systems to increase bean yields; however, there has been little research conducted on management systems that alleviate the above-mentioned constraints. Agronomic practices that maximize bean production are not commonly used in Uganda even though some agronomic practices such as planting in rows and more frequent weeding can be implemented with little or no capital investment. The conventional system of planting beans is scatter-planting seeds at a density of about 10 seeds m^{-2} (Mazur et al., 2014). Scatter-planting consists of randomly digging shallow holes throughout a field with a hand hoe and dropping a seed in the hole before covering the seed with soil. This method could be improved to planting beans in rows at an increased optimum density of 20 seeds m^{-2} (Uganda Export Promotion Board, 2005) because beans in rows are easier to manage for pests such as weeds, insects, and diseases. Improved control of competitive weeds is especially important during the period up to flowering as weeds compete for water, nutrients, and light (Graham and Ranalli, 1997; Ugen and Wortmann, 2001). Weeds decrease bean nutrient uptake and growth and when left uncontrolled can significantly decrease the leaf area index (LAI) and yield (Ugen et al., 2002).

Bean yields and soil quality have declined in Uganda over the past two decades (Bekunda et al., 2002), partly due to increased cropping intensity and lack of longer-term bush fallow (Chianu et al., 2011; International Food Policy Research Institute, 2014). Fertilizer additions can overcome specific nutrient deficiencies, but fertilizers are expensive investments in sub-Saharan Africa, including rural Uganda, and most farmers use low levels or no fertilizer at all (Bekunda et al., 2002; Chianu et al., 2011; Lunze et al., 2012), contributing to further nutrient depletion of soil. Fertilizing bean can increase root growth providing improved access to soil water (Beebe et al., 2014) and nutrients. Soil testing of available nutrients is rarely done by smallholder farmers in sub-Saharan Africa but it is important to be aware of crop nutrient needs, especially nitrogen, phosphorus, and potassium, which are commonly deficient in these soils (Bekunda et al., 2002; Margaret et al., 2014; Sinclair and Vadez, 2012; Wortmann et al., 1998a).

Nitrogen is needed in large quantities because it is an important component of all proteins and nucleic acids necessary for new, functioning cells (Sinclair and Vadez, 2012). Bean is generally considered to be a poor N fixer (Hardarson et al., 1993; Graham and Ranalli, 1997) but inoculation with appropriate *Rhizobium* spp. can increase grain yields in East Africa (Maingi et al., 2001). High levels of N fixation have been documented when the crop is not limited by other constraints (Giller et al., 1998; Giller and Amijee, 1998; Hardarson et al., 1993), and for that reason it is very important to address low soil P to prevent severely reducing symbiotic nitrogen fixation (SNF) or limiting root expansion (Graham and Ranalli, 1997; Beebe et al., 2014). Adequate K is required for improved tolerance to drought stress, protection against biotic stresses, optimal growth and productivity (Oosterhuis et al., 2014), and as cropping intensifies and higher amounts of K are exported from the field (Mengel and Kirkby, 1980). Potassium is frequently removed in large amounts from fields in sub-Saharan Africa because crop residues are typically removed from the field at harvest rather than incorporated or left on the soil surface (Giller et al., 2009), further worsening K soil deficiency (Oosterhuis et al., 2014). Extensive, long-term production of banana in Africa also exacerbates K deficiency due to the very large amounts of K removed in banana and plantain fruit (*Musa* spp.) (Lahav and Lowengart, 1998). The addition of K can increase the competitiveness of bean and therefore may also be important for weed management (Ugen et al., 2002).

Additional constraints to bean production by smallholder farmers were shown by Mazur et al. (2014), who documented strong negative effects of foliar disease on bean yield in south-central Uganda. Quality seed, free from disease, is a prerequisite for high bean yield (Graham and Ranalli, 1997). The application of foliar or seed-applied fungicides can decrease the impacts of diseases; however, the development and deployment of bean cultivars with improved host plant resistance to commonly occurring diseases has been one of the most important strategies to improving bean yield (Sinclair and Vadez, 2012). Cultivars that are disease resistant offer a form of protection to farmers who are less likely to be able to afford pesticides and pathogen-free seed (Graham and Ranalli, 1997).

Bekunda (2004) and Esilaba (2005) expressed the need for farmers to reverse soil nutrient depletion through better management of their soils and cropping systems. The development of improved management systems that alleviate the aforementioned constraints is necessary to improve grain yield and profitability. To address these issues, we developed a study with the objective of comparing grain yield and profitability of four bean cultivars grown under a conventional and two improved management systems in order to determine which cultivar and system combination is the most productive and profitable on Liddugavu (Phaeozem) soil in south-central Uganda.

2. Materials and Methods

2.1 Experimental site

The experimental site was located approximately 13 km northeast of Masaka, Central Region, Uganda (latitude 0^{o} 15’ 45.6228” S; longitude 31^{o} 48’ 49.8708” E; altitude 1253 m). The climate is tropical with a bimodal rainfall pattern (Jones et al., 2013). Soil at the location is called Liddugavu (black) in the local language, but is defined as a Phaeozem using the FAO-UNESCO soil legend and as a Hapludoll using USDA Soil Taxonomy (FAO, 1988; USDA NRCS, 1999). The soil at the experimental site was a sandy clay loam texture and formed from alluvial deposits. Prior to adding soil amendments, soil at the 0 to 15 cm depth had a pH range of 6.6 to 6.8, Mehlich-3 P ranged from 20 to 30 mg kg^{-1}, and organic matter ranged from 36 to 37 g kg^{-1}. Long term mean annual precipitation in Uganda is 1175 mm, with about 86 percent occurring during the two crop growing seasons (World Bank Group, 2015). Precipitation data for the specific research site were not available before this project. According to the landowner, prior to the initiation of this study, the site had been in a maize (*Zea mays*), bean (*Phaseolus vulgaris* L.), groundnut (*Arachis hypogaea*), banana (*Musa* spp.), and cassava (*Manihot esculenta*) intercrop.

2.2 Experimental design

The study was initiated in July 2014 and continued over two seasons, the second rainy season of 2014 (2014B), from the end of August through the beginning of December, and the first rainy season of 2015 (2015A), from the end of March through the middle of June. The experimental design was a randomized incomplete block in a split-plot arrangement. Management system was the whole-plot factor and included the Conventional Farmer System (CFS), Improved Farmer System (IFS), and High Input System (HIS) (Table 1). The subplots were four bush type common bean cultivars. Two cultivars were new and improved, NABE 14 and NABE 15, and two were conventional cultivars, K132 and NABE 4 (Table 2). The new cultivars were released 7 to 16 years later (2006 & 2010) than the older cultivars (1994 &1999) and have greater resistance to several bean diseases prevalent in the south-central region of Uganda. Individual subplot size measured six by four m. There were four replications of each management system × cultivar subplot combination, except for three subplots, which were excluded due to limited land availability. Replications were blocked perpendicular to the slope.

2.3 Crop management practices

Perennial crops and residual weeds from the previous rainy season were removed using a hand hoe more than one month prior to planting in the 2014B season. Ground agricultural limestone with 68.85 percent effective calcium carbonate equivalent (ECCE) containing 38 percent Ca, 0.29 percent Mg, 0.10 percent S, and 1.24 percent P was applied at 295 kg ha^{-1} to supply Ca at 112 kg ha^{-1}. Potassium was not applied in the 2014B season because results from preliminary soil tests in January 2014 showed adequate levels (Liebenberg, 2002). Post-harvest soil results showed available K was as low as 74 mg kg^{-1} in some plots, therefore muriate of potash was broadcast by hand prior to tillage in the 2015A season at 112 kg K_2O ha^{-1} in the IFS and HIS. One to two weeks prior to planting, tillage was conducted with a hand hoe to a depth of 15-20 cm over a period of several days. Beans planted in the CFS were scatter planted at a density of 10 seeds m^{-2} while beans in the IFS and HIS were planted in rows 50 cm wide with seeds planted every 10 cm, which resulted in the recommended planting density of 20 seeds m^{-2} for both the IFS and HIS (Uganda Export Promotion Board, 2005). The 10 seeds m^{-2} rate for the CFS was determined by extensive sampling of farmer bean fields in Masaka District the previous rainy season, 2014A (Mazur et al., 2014)

Bean seeds were obtained from Community Enterprises Development Organisation (CEDO, Rakai, Uganda). Seed for the HIS were treated with VITAVAX® (Bayer CropScience, Research Triangle Park, NC.) fungicide (carboxin: (5,6-Dihydro-2-methyl-N-phenyl-1,4-oxathiin-3-carboxamide) by CEDO personnel. Seeds planted in the HIS were inoculated with Mak-Bio-Fixer rhizobia obtained from Makerere University prior to planting. Before planting, triple superphosphate (0-46-0) was banded at 33.6 kg

P_2O_5 ha^{-1} in the IFS and the HIS in the 2014B season and at 44.8 kg P_2O_5 ha^{-1} in these improved management systems in the 2015A season. Bands were placed in hand dug furrows at a depth of 8-10 cm and covered with 2-4 cm of soil, similar to the technique described by Lunze et al. (2012). Beans were then placed at the recommended depth of 3-5 cm (Liebenberg, 2002; Amongi et al., 2014) before being covered with soil using a hand hoe. Beans were planted on 19 and 20 August during the 2014B season and 24 and 25 March during the 2015A season.

Formulated azoxystrobin (methyl (E)-2-{2[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate) was applied as a foliar fungicide at 458 g ha^{-1} to the HIS both seasons. The fungicide was applied using a hand-pumped backpack sprayer in approximately 625 L H_2O ha^{-1} at the early stages of R8 pod filling in the 2014B season and at the late stages of R7 pod formation in the 2015A season. Four days after applying the fungicide in the 2014B season, the insecticide cypermethrin ((±) α-cyano-(3-phenoxyphenyl)methyl(±)-*cis-trans*-3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate) formulated as Dudu-Cyper® 5 percent EC (Bukoola Chemical Industries LTD, Kampala, Uganda) was foliar-applied to the HIS beans at a rate of 2.5 L ha^{-1} and applied with the same hand-pumped backpack sprayer in approximately 625 L H_2O ha^{-1}. Control of aphids was not needed in the 2015A season, therefore cypermethrin was not applied.

Weeding was done by hand between plants and with a hand hoe between rows twice per season for the CFS and IFS. The first weeding was done at V3 in the 2014B season and between V3 and V4 in the 2015A season. The second weeding occurred between R7 and R8 both seasons. Weeding was done weekly for the HIS, using the same method, so that weeds were never competitive with beans.

2.4 Crop and soil data collection

The pre-amendment and post-harvest soil samples were collected at a depth of 0 to 15 cm from 12 subsamples collected from each replication of each whole-plot. Soil samples were analyzed for pH and electrical conductivity (EC) using the potentiometric method. Extractable aluminum, organic matter, and N concentrations were determined by colorimetry. The cation exchange capacity (CEC) was calculated according Brady and Weil (2007). After extraction with Mehlich-3 inductively coupled plasma optical emission spectrometry (ICP-OES), soil samples were analyzed for P, K, Mg, Ca, Na, Al, Mn, S, Cu, B, Zn, and Fe; the C:N ratio was calculated.

Phenological development stages were recorded weekly in each plot using the standard system developed for common bean (Fernandez et al., 1986; Van Schoonhoven and Pastor-Corrales, 1987). Between R8 and R9, aboveground crop biomass was determined by hand clipping five bean plants per plot. Bean biomass samples were placed into labelled bags for transport to Makerere University for oven drying. Biomass samples were oven-dried at 60˚C for 7 days and then weighed. The yield, yield components, and extended plant height data were collected from all bean plants within the area harvested from each plot. The area harvested in the CFS was selected by randomly placing two 1.0 m^2 quadrats in each plot (2.0 m^2 total). The IFS and HIS yield samples were determined from two 2-meters of row in each plot (2.0 m^2 total). Stand density of bean at the R9 stage was determined at harvest by counting the number of plants within each harvested area. Extended plant height was measured on every plant harvested, up to a maximum of ten plants per subplot. At harvest, all pods were hand-picked, counted, placed in a paper bag, and brought to a scale to be weighed. Pods were taken to Makerere University where they were placed in an oven at 60˚C until dry. The grain was then shelled from pods by hand, counted, and weighed. The pod harvest index (PHI; dry weight of seed at harvest/dry weight of pod at harvest × 100), pod number per area (pods m^{-2}), and seed number per pod (seeds pod^{-1}) were computed as described by Beebe et al. (2013). Reported grain yields represent oven-dried weight.

Soil volumetric water content (VWC) was determined using a FIELDSCOUT® TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Plainfield, IL). Sampling occurred weekly in each subplot at two points for each of the two depths, 7.5 and 20 cm.

The costs of production and market prices of beans were determined using local market prices for all of the agricultural inputs, except rhizobia, which was unavailable in the local market. Rhizobia inoculant was available at Makerere University; it was assumed inoculation will occur every four seasons. The economic return to labor and management (ERLM) was determined using land rental costs collected from the Farmer Decision Making Strategies for Improved Soil Fertility Management in Maize-Bean Production Systems project (Mazur et al., 2014, 2015), which provided a representative cost in this region. The market price of bean used in this analysis assumed beans were sold immediately after harvest when farm gate prices ranged from 1500 to 1700 UGX kg^{-1}, depending on the bean cultivar. The UGX to USD conversion rate used for this study was 3400 UGX = 1 USD.

2.5 Statistical analysis

Data were analyzed as a randomized incomplete block in a split-plot arrangement with management system as the whole-plot factor and bean cultivar as the subplot factor. Statistical analyses for yield, yield components, height, biomass, PHI, VWC, phenological, and economic data were performed with the GLIMMIX Procedure of SAS V9.4 (SAS Institute, 2013). Least squares means were generated for all variables when significant F values ($P < 0.05$) were observed and then separated using the LINES option at $P = 0.05$. Soil data were analyzed using PROC GLM, which enabled us to separate means using the multiple mean comparison of the protected least significant difference. Differences among treatments were reported as significant at $P = 0.05$ except for the phenological differences between treatments, which were reported as significant at $P = 0.01$. Management system, cultivar, rainy season, and weeks after planting (WAP) were treated as fixed effects. Replication, replication × management system, and cultivar × replication × management system were considered random effects for analyses of crop, soil, and economic data.

3. Results

3.1 Climate

Long-term mean annual precipitation for this region is 1175 mm, 86% of which occurs during the crop growing season (Table 3) (World Bank Group, 2015). Total precipitation during our study, July 2014 through June 2015, was 1381 mm, 18% greater than the long-term mean. Precipitation during the dry season months, July and again

January through February, amounted to only 67% of the 22-yr average for these months. However, the precipitation in April 2015 was 139% greater than that of the long-term average and the precipitation in May 2015 was 131% greater than that of the long-term average. Mean long term monthly air temperature ranged from a low of 22.3^{o}C in July to a high of 24.9^{o}C in February (World Bank Group, 2015). Temperature data were not collected at our research site during the period of this study.

3.2 Soil

The pre-amendment soil results did not show differences among management systems; however, there were greater levels of extractable Al, Cu, Fe, N, and Mn in the post-harvest soil data compared to the pre-amendment soil data (Table 4). Additionally, post-harvest soil results had differences in available copper among management systems. The IFS had seven and ten percent more copper than the HIS and CFS, respectively. The available P, K, and Ca were similar between management systems across both sampling dates despite receiving different amounts of each as soil amendments.

3.3 Volumetric water content

The VWC differed for rainy season and the interaction of rainy season × depth. All other main effects and interactions were not significant. There was an interaction of rainy season × depth for VWC over two seasons. VWC differed for depth in both seasons. Mean VWC in the 2014B season was 0.20 cm^3 cm^{-3} and 0.23 cm^3 cm^{-3} for 7.5 cm depth and 20 cm depth, respectively while mean VWC in the 2015A season was 0.30 cm^3 cm^{-3} and 0.27 cm^3 cm^{-3} for 7.5 cm depth and 20 cm depth, respectively. The 2014B season was wetter at 20 cm depth compared to 7.5 cm depth while the reverse was true for the 2015A season.

3.4 Phenological growth stages

The phenological growth stages of beans varied for cultivar, rainy season, weeks after planting (WAP), and the interaction of cultivar × rainy season, cultivar × WAP, rainy season × WAP, and cultivar × rainy season × WAP (Fig. 1). In the 2014B season, there was a trend for faster development of NABE 15 while the other cultivars developed at a similar rate, more slowly than NABE 15, and reached maturity in 13 weeks. In the 2015A season, development rates were similar for the four cultivars, although maturity was reached in only 11 weeks (Fig. 1). There was a diverging trend of NABE 15 both seasons at five WAP and converging again a couple weeks later. Then around 10 WAP both seasons, NABE 15 converged at maturation (R9).

3.5 Yield, yield components, height, biomass, and pod harvest index (PHI)

At maturity (R9 stage), stand density of beans differed for management system, cultivar, and the interaction of cultivar × rainy season (Table 5). Stand density differed for cultivars under both rainy seasons. NABE 14 was among the greatest for stand density both seasons while NABE 15 had the lowest density in both rainy seasons (Table 6).

Height of beans at harvest varied for cultivar, rainy season, and the interactions of management system × rainy season and cultivar × rainy season (Table 5). In the 2014B season, beans had similar height under all management systems (Table 7). Conversely, beans in the 2015A season under the HIS were taller than beans under the CFS; height of beans in the IFS was intermediate and not different from either the CFS or HIS. The NABE 14 and K132 were the tallest cultivars in the 2014B season and the 2015A season; NABE 15 was the shortest entry for both rainy seasons (Table 6).

Pod density of beans differed for management system, cultivar, rainy season, and the interactions of management system × rainy season, cultivar × rainy season, and management system × cultivar × rainy season (Table 5). In the 2014B season, pod density increased with increasing input level (Fig. 2). In the 2015A season, this same trend occurred with NABE 14 and K132. Conversely, in the 2015A season, pod density of NABE 15 and NABE 4 did not increase with increasing input levels. The interaction of management system × cultivar was not significant in the 2014B season; though this interaction was significant in the 2015A season. Cultivars did not differ for pod density within management systems in the 2014B season. On the other hand, in the 2015A season, cultivars differed among management systems for pod density. NABE 14 produced more pods m^{-2} than all other cultivars within each management system in the 2015A season while NABE 15 had the least or was among the least for pod density within each management system.

Seed number pod^{-1} varied for cultivar, rainy season, and the interaction of cultivar × rainy season (Table 5). Seed number pod^{-1} varied for cultivar both rainy seasons (Table 6). In both rainy seasons, NABE 14 frequently produced more seeds pod^{-1} than the other cultivars while NABE 15 frequently produced fewer seeds pod^{-1} than the other cultivars.

The 100-seed weight varied for cultivar and rainy season; however, the interactions were not different (Table 5). Management system did not influence 100-seed weight but the seed weight across management systems in the 2014B season was 15% greater than for the 2015A season. K132 and NABE 4 produced the heaviest seeds, weighing 14 and 16% greater than NABE 15, respectively.

Aboveground biomass (g plant^{-1}) varied for cultivar, rainy season, and the interactions of management system × rainy season and cultivar × rainy season (Table 5). In the 2014B season, beans in the CFS accumulated 28 and 33% greater biomass than beans under the IFS and HIS, respectively, but differences were not significant among management systems for biomass in the 2015A season (Table 7). The interaction of cultivar × rainy season was not significant in the 2014B season; however, this interaction was significant in the 2015A season (Table 6). In the 2015A season, NABE 14 accumulated 260, 125, and 200% greater biomass than NABE 15, K132, and NABE 4, respectively.

Grain yield differed for management system, cultivar, rainy season, and the interactions of management system × rainy season, cultivar × rainy season, and management system × cultivar × rainy season (Table 5). In the 2014B season, grain yield increased with increasing input level (Fig. 2). In the 2015A season, this same trend occurred with NABE 14 and K132. However, for this rainy season, grain yield of NABE 15 and NABE 4 did not increase with increasing input levels. In the 2014B season, yields were similar among cultivars within each of the three management systems. In the 2015A season, NABE 14 produced greater yields than the other three cultivars within the IFS and HIS while NABE 4 and NABE 15 produced among the lowest grain yields in these management systems. NABE 14 produced 444% greater yield than NABE 15 under the CFS in the 2015A season.

The PHI varied for cultivar but no other treatment factor or interaction was significant (Table 5). The PHI for NABE 15 was 11% greater than for NABE 14 but was not different from the other two cultivars.

3.6 Economic analysis

Management system and the interaction of management system × cultivar did not influence the economic return to labor and management (ERLM); however, cultivar, rainy season, and the interactions of management system × rainy season, cultivar × rainy season, and management system × cultivar × rainy season were significant and influenced ERLM (Table 5). In the 2014B season, net profit was greatest for the HIS (Fig. 3). In the 2015A season, the CFS produced greater profits than the IFS while the HIS was intermediate and did not differ from the CFS or IFS. In the 2014B season, net profits were similar among cultivars within the CFS but differed for IFS and HIS. Of the four cultivars tested in the HIS in the 2014B season, NABE 14, NABE 15, and NABE 4 produced greater profits than K132. Over both seasons, NABE 14 remained profitable in all six management system × cultivar × rainy season combinations and showed greater positive returns than any other cultivar. In the 2015A season, NABE 15 produced among the greatest net losses in each management system; NABE 14 produced \$200 ha^{-1}, \$406 ha^{-1}, and \$678 ha^{-1} greater profits than NABE 15 within the CFS, IFS, and HIS, respectively. About 58, 88, and 90% of the total cost of production comes from agricultural inputs in the CFS, IFS, and HIS, respectively (results not presented).

4. Discussion

4.1 Climate, volumetric water content, and phenological growth stages

Precipitation during the 2014B season was normal and all other environmental conditions were suitable for good growth of beans; however, precipitation during the 2015A season was abnormally intense and frequent, resulting in unusually long periods of high VWC in the early part of the growing season, which may have caused the soil surface to have greater VWC. The increase in soil VWC may have led to the greater frequency of diseases (results not presented) and damping-off (Athanase et al., 2013) in the 2015A season, which appeared to be related to the reduction in R9 plant stands and overall lower grain yield compared to the 2014B season (Fig. 2). It was also believed that the VWC would increase with increased management level because the IFS and HIS had greater planting density, which enabled them to canopy quicker and therefore prevent soil water loss through evaporation; however, significant differences were not observed.

The differences in phenological development between cultivars at each date were likely due to the differences in maturity groups between the four cultivars. NABE 15 was a short maturity cultivar, while K132 was an intermediate, and NABE 14 and NABE 4 were long maturity cultivars (Table 2).

4.2 Management and cultivar selection

Farmers prefer to plant common bean on Liddugavu soil if it is available because they have recognized this soil is generally more fertile than other soils, providing a better growing environment for beans (Mazur et al., 2014). Because the Liddugavu soil type is considered fertile, these soils typically receive little or no fertilizer applications for bean production under the current management systems used by farmers. As a result, bean yield on this soil is much lower than its potential.

Beans were planted at an increased density to promote faster canopy closure which prevents soil water evaporation, shades out weeds, and captures more light. We replanted beans on the same plots both seasons to develop a better understanding of nutrient carry-over effects within each management system. Doing this also allowed us to determine yield response of improved management systems in a bean-bean rotation which many smallholder farmers are now practicing due to limited land resources (Ampofo et al., 2001). Because land is limited, beans are sometimes intercropped with maize in this region but we chose to develop two improved sole crop bush bean production systems because previous research in East Africa by Maingi (2001) and Kimani et al. (2010) documented that bean yields are significantly reduced if intercropped with other crops.

Bush bean cultivars were employed in this study because these cultivars are the most prevalent type in this region. Three of the four cultivars (K132, NABE 4, and NABE 15) in this study were the most popular cultivars grown in Uganda (Kilimo Trust, 2012), which was confirmed in this region with a survey conducted by Mazur et al. (2014). NABE 14 was included in this study because this was a newer cultivar with tolerance to low soil fertility and resistance to angular leaf spot (*Phaeoisariopsis griseola*) (ALS), bean common mosaic virus (*Poryvirus* spp.) (BCMV), and root rots (*Fusarium solani* f. sp. *phaseoli*); therefore, this cultivar had a better yield potential under greater disease pressure (Table 2). The beneficial effects of host plant resistance to foliar and root diseases in NABE 14 were apparent in the abnormally wet 2015A season. To our surprise, NABE 15 grain yields were very poor for a newly released cultivar, especially during the 2015A season. Nonetheless, this cultivar was also documented by Mazur et al. (2012) as low yielding. This shows us that not all improved cultivars perform well under every environment and it is therefore our recommendation that multiple cultivars are included in subsequent studies. NABE 15 and the older cultivars, K132 and NABE 4, likely produced lower yields than NABE 14 because they are susceptible to root rots, which were noted in the wet 2015A season.

There are many tradeoffs to consider when selecting bean cultivars. Ugandan farmers choose which cultivars to grow based on soil fertility conditions, tolerance or resistance to heavy rainfall or drought, maturity, cooking time, taste, market prices, marketability, and productivity (Mazur et al,, 2012; Kilimo Trust, 2012). Although NABE 14 is a very reasonable choice with a high potential for grain yield, this cultivar has a major disadvantage in requiring a longer cooking time compared to some local cultivars and therefore requires more fuel for meal preparation (Mazur et al., 2012). Conversely, the lowest producing cultivar, and one of the most popular among consumers, NABE 15, requires among the shortest cooking time, a preferred trait in Uganda (Mazur et al., 2012; Graham and Ranalli, 1997). It is also important to note that the lower yielding cultivars sometimes bring a higher market price.

4.3 Agricultural inputs and soil nutrient status

Potassium fertilizer was not applied in the 2014B season because preliminary soil data showed extractable K was adequate for bean production. However, mid-season, pre-amendment soil nutrient results became available that documented soil was deficient in both P and K. Determining fertilizer application was challenging because very little work has been done on fertilizer recommendations in Uganda, especially for individual soil types within different regions of the country (Benson et al., 2013). Additional studies should develop recommendations for fertilizer application rates based on test values within each region of Uganda because current recommendations broadly recommend fertilizer rates for entire regions or soil types irrespective of management history or actual nutrient status.

Nitrogen can be supplied to beans by N fixation following inoculation of seeds with appropriate *Rhizobium* spp., offering a cost effective alternative to N fertilizers (Hardarson and Atkins, 2003) or soil mining. Even with good N fixation, several reports suggest that beans may be nitrogen limited without supplemental nitrogen application (Liebenberg, 2002; Wortmann et al., 1998b); however, we decided to inoculate our seeds in the HIS and not apply nitrogen because beans have been shown to fix nitrogen at rates greater than 100 kg ha^{-1} under optimum conditions (Graham and Ranalli, 1997; Hardarson and Atkins, 2003). Optimum conditions generally occur under P fertilization and liming, which is appropriate to ameliorate low pH or Ca deficiency (Giller et al., 1998; Lunze et al., 2012; Wortmann et al., 1998b). We attempted to create optimal conditions for N fixation in the HIS by applying lime (38% Ca) and P fertilizer. Nitrogen deficiency was only noted in one HIS plot, suggesting nitrogen needs were not limiting following rhizobia inoculation. Even though both improved management systems received P and lime applications, the post-harvest soil results unexpectedly showed no differences in P or Ca concentrations compared to the pre-amendment soil results. This could be attributed to increased plant uptake or P being complexed by reactions in the soil (Fungo et al., 2011; International Food Policy Research Institute, 2014).

4.4 Pests and diseases

Lower yields across management systems, cultivars, and the management system × cultivar interaction were expected in the 2015A season because our study was conducted on the same plots as the previous season. Disease prevalence was greater in the 2015A season which may have been due to the bean-bean rotation or the greater amounts of rain and increased number of rainy days compared to the 2014B season (Athanase et al., 2013). Increased frequency and amount of rain in the 2015A season may have also been the cause for the decreased presence of aphids (Weisser et al., 1997).

4.5 Economic analysis

Although the ERLM results in this study did not consistently show an increase in net profits by increasing input levels, improved yields document there is great potential for increased profits with improved management systems if input costs decrease and/or grain prices increase. Uganda currently imports many of its agricultural inputs such as fertilizers, lime, pesticides, and herbicides (International Food Policy Research Institute, 2014), which is very costly since Uganda is a land-locked country. It currently takes more than 24 hours of overland transportation to reach a major port to gain access to world markets, which not only increases the cost of agricultural inputs but also impacts the price of Ugandan beans at the farm gate (International Food Policy Research Institute, 2014). Due to the lack of quick and inexpensive transport to world markets, the demand for Ugandan beans is low and therefore grain prices remain low. This is one of the major reasons why only 20% of Uganda's bean production is exported while the rest is traded or consumed locally (Kilimo Trust, 2012).

Improved management systems were more labor intensive due to the labor required for applying inputs, and if labor was hired it would represent approximately 50 percent of the total cost of production in this study. However, there is great variability in labor costs due to the inconsistency of prices between villages, field locations, presence or absence of weeds, relationship with farmers, and seasonal demand. Therefore, different results might have been obtained in other areas of the country. The ERLM does not include the cost of labor in the economic analysis because most labor on smallholder farms in this region of Uganda is provided free of charge by members of the family. Furthermore, the opportunity cost for these family members is very low because there are very few opportunities for off-farm employment; therefore, the ERLM was included in the economic analysis instead of the economic return to management.

A significant portion of the total production costs were from imported and expensive agricultural inputs, especially agricultural lime. With current bean values, production costs, and production levels it may not always be profitable at this time for smallholder farmers to invest in expensive agricultural inputs such as mineral fertilizers to replenish or maintain soil nutrient reserves or alleviate soil infertility, which agrees with the conclusions of an analysis presented by Nabhan et al. (1999). This is especially important in a region experiencing extensive changes in rainfall patterns in recent years, because these management systems may not recover the value of the fertilizer or other inputs (Ojiem et al., 2014; Page and Chonyera, 1994).

Regarding cultivar selection, the improved cultivar NABE 14 had the potential for greater returns than other bean cultivars due to its ability to produce higher yields under varying levels of fertility, moisture stress, and pest and disease pressure. This cultivar may become even more profitable in the future as transport to the world markets via sea ports becomes quicker and cheaper due to ongoing infrastructure improvements (Nkonya et al., 2005). Similar to our analysis for profitability, Broughton et al. (2003) compared newly released and older bean cultivars and reported profits increased 300 percent or more with the use of improved cultivars in Central and South America. Although not mentioned by Broughton et al., it was assumed that farmers in these countries had a greater earning potential than farmers in Uganda because their countries were not land-locked countries and had greater access to world markets and less expensive inputs. Subsidized agricultural inputs for bean may offset the high cost of production and encourage better management of soils. This will promote greater bean yields and therefore consumption, resulting in improved human health and ultimately improving the livelihoods for the smallholder farmers.

To reduce risk for bean production in south-central Uganda, rainy season B is better suited for bean production, both in terms of yield and profit. Farmers may want to hedge their risk by investing in improved bean management practices only in rainy season B where the rains are more favorable for bean production due to lower intensity rainfall compared to rainy season A. Furthermore, farmers may find it financially beneficial to plant an improved cultivar such as NABE 14 due to its ability to produce well in many environments and therefore a higher probability of providing greater return on investment.

We hypothesized that improved bean cultivars could increase grain yields, especially under greater input levels and management practices. Our production results support conclusions from the Uganda Export Promotion Board (UEPB) (2005), which stated that higher input systems provided greater yields than subsistence bean management systems and low input systems. However, our ERLM results differ from those of the UEPB because our results did not consistently show a greater return on investment as input and management levels increased.

Another strategy to increasing profit is to store beans in Jerricans or Triple Bags for 90 days after harvest because a recent study by Mazur et al. (personal communication, 2015) reported an increase in the farm gate price by more than 50% by waiting 90 days to sell. Inserting the 50% higher price of beans into our dataset showed it is more profitable to utilize improved management systems and greater returns on investment were then found for the HIS when compared to the CFS and IFS under the ERLM analysis.

Our systems research approach confounds agricultural inputs and pest management practices within each improved management system making it difficult to determine exactly which inputs or practices were responsible for the improvements in yield. Nonetheless, this approach allows for rapid assessment and comparison of multiple bean management systems, both for productivity and profitability, prior to widespread testing in farmer-led research.

5. Conclusions

Increasing management level and planting bean cultivars resistant to common bean diseases improved grain yield in both rainy seasons. The increase in yield can most likely be attributed to the differences in planting arrangement and density, fertilizer application, improved N fixation, and weed and pest management. All inputs were obtained locally, except the rhizobia inoculant, suggesting that increased yields and profitability are obtainable by farmers, especially when utilizing NABE 14 under the HIS. Rainy season A experienced unfavorable precipitation for bean production and according to our results it is not recommended for bean production. Agricultural input prices were too high while farm gate prices for beans were too low to propose widespread adoption of high input management systems by smallholder farmers. However, our production results suggest that common bean production systems that increase the use of agricultural inputs and improved pest management strategies are acceptable methods for farmers to alleviate constraints limiting bean production, the most important source of dietary protein and iron nutrition in south-central Uganda.

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References

Ampofo, J.K.O., Hollenweger, U., Massomo, S.M., Ulicky, E., 2001. Participatory IPM development and extension: the case of bean foliage beetles in Hai, Northern Tanzania. Pan-African Bean Research Network (PABRA) Millennium Workshop, 28 May-1 June, Arusha, Tanzania, CIAT, Kampala, pp. 87-95.

Amongi, W., Nkalubo, S.T., Ochwo-Ssemakula, M., Gibson, P., Edema, R., 2014. Development of intermittent drought stress tolerant common bean genotypes in Uganda. Afr. Crop Sci. J. 22, 303–315.

Assefa, T., Beebe, S.E., Rao, I.M., Cuasquer, J.B., Duque, M.C., Rivera, M., Battisti, A., Lucchin, M., 2013. Pod harvest index as a selection criterion to improve drought resistance in white pea bean. Field Crops Res. 148, 24–33.

Athanase, C., Tenywa, J.S., Tenywa M.M., Okiror, J.J., Leonidas, D., Mupenzi, M., Augustine, M., 2013. Farmers' Coping Mechanisms for Common Bean Production under Water-Logged Soil Conditions in Uganda-Rwanda Boarder Region. J. Environ. Sci. Eng. B. 2, 46-52.

Beebe, S., Rao, I., Devi, M., Polania, J., 2014. Common beans, biodiversity, and multiple stress: challenges of drought resistance in tropical soils. Crop Pasture Sci. 65, 667-675.

Beebe, S.E., Rao, I.M., Blair, M.W., Acosta-Gallegos, J.A., 2013. Phenotyping common beans for adaptation to drought. Front. Physiol. 4, 1–21.

Bekunda, M.A., Nkonya, E., Mugendi, D., Msaky, J.J., 2002. Soil fertility status, management, and research in East Africa. East Afr. J. Rural Dev. 20, 94–112.

Benson, T., Lubega, P., Bayite-Kasule, S., Mogues, T., Nyachwo, J., 2013. The Supply of Inorganic Fertilizers to Smallholder Farmers in Uganda: Evidence for Fertilizer Policy Development. Uganda Strategy Support Program. IFPRI. Policy Note 16.

Brady, N.C., Weil, R.R., 2007. The colloidal fraction: seat of soil chemical and physical activity, in: The Nature and Properties of Soils, 14th ed. Prentice Hall, pp. 310–357.

Broughton, W.J., Hernández, G., Blair, M., Beebe, S., Gepts, P., Vanderleyden, J., 2003. Beans (*Phaseolus* spp.) – model food legumes. Plant Soil 252, 55–128.

Chianu, J.N., Chianu, J.N., Mairura, F., 2011. Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agron. Sustain. Dev. 32, 545–566.

CIAT (Centro Internacional de Agricultura Tropical), 1989. Bean Production Problems in the Tropics. 2nd ed. Schwartz, H.F. and Pastor-Corrales, M.A. (eds.). Cali, Columbia. 726 p.

Esilaba, A.O., Nyende, P., Nalukenge, G., Byalebeka, J.B., Delve, R.J., Ssali, H., 2005. Resource flows and nutrient balances for crop and animal production in smallholder farming systems in eastern Uganda. Agric. Ecosyst. Environ. 109, 192–201.

FANTA-2, 2010. The Analysis of the Nutrition Situation in Uganda, Food and Nutrition Technical Assistance II Project (FANTA-2). Washington, DC. http://www.fantaproject.org/sites/default/files/resources/Uganda_NSA_May2010.pdf, Electronic source, accessed on 17 December, 2015.

FAO, 2010. Uganda Nutrition Profile - Nutrition and Consumer Protection Division. ftp://ftp.fao.org/ag/agn/nutrition/ncp/uga.pdf, Electronic source, accessed on 17 December, 2015.

FAO, 1988. FAO/UNESCO Soil Map of the World. Revised Legend, with corrections and updates.

Fernandez, F., Gepts, P., Lopez, M., 1986. Stages of development of the common bean plant; study guide to be used as a supplement to the audio tutorial unit on the same topic. CIAT. Cali, Colombia. 32p. (Series 04EB-09.03).

Fungo, B., Grunwald, S., Tenywa, M., Vanlauwe, B., Nkedi-Kizza, P., 2011. Lunnyu soils in the Lake Victoria basin of Uganda: Link to toposequence and soil type. Afr. J. Environ. Sci. Technol. 5, 15–24.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Res. 114, 23–34.

Giller, K.E., Amijee, F., 1998. Environmental constraints to nodulation and nitrogen fixation of *Phaseolus vulgaris* L. in Tanzania. I. A survey of soil fertility, root nodulation and multi-locational responses to rhizobium inoculation. Afr. Crop Sci. J. 6, 159–169.

Giller, K.E., Amijee, F., Brodrick, S.J., Edje, O.T., 1998. Environmental constraints to nodulation and nitrogen fixation of *Phaseolus vulgaris* L. in Tanzania. II. Response to N and P fertilizers and inoculation with rhizobium. Afr. Crop Sci. J. 6, 171–178.

Graham, P.H., Ranalli, P., 1997. Common bean (*Phaseolus vulgaris* L.). Field Crops Res. 53, 131–146.

Hardarson, G., Atkins, C., 2003. Optimising biological N_2 fixation by legumes in farming systems. Plant Soil 252, 41–54.

Hardarson, G., Bliss, F.A., Cigales-Rivero, M.R., Henson, R.A., Kipe-Nolt, J.A., Longeri, L., Manrique, A., Peña-Cabriales, J.J., Pereira, P.A.A., Sanabria, C.A., Tsai, S.M., 1993. Genotypic variation in biological nitrogen fixation by common bean. Plant Soil 152, 59–70.

International Food Policy Research Institute, 2014. Atlas of African agriculture research and development. http://www.ifpri.org/publication/atlas-african-agriculture-research-development, Electronic source, accessed on 17 December, 2015.

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M., Zougmoré R., (eds.), 2013. Soil Atlas of Africa. European Commission, Publications Office of the European Union, Luxembourg. 176 pp.

Kilimo Trust, 2012. Development of Inclusive Markets in Agriculture and Trade (DIMAT): The Nature and Markets of Bean Value Chains in Uganda. http://www.undp.org/content/dam/uganda/docs/UNDP%20Uganda_PovRed%20-%20Beans%20Value%20Chain%20Report%202013.pdf, Electronic source, accessed on 17 December, 2015.

Kimani, P.M., Buruchara, R.A., Ampofo, K., Pyndji, M., Chirwa, R., Kirkby, R., 2001. Breeding beans for smallholder farmers in Eastern, Central, and South Africa: Constraints, achievement and potential. Pan-African Bean Research Network (PABRA) Millennium Workshop, 28 May-1 June, Arusha, Tanzania, CIAT, Kampala, pp. 11-28.

Lahav, E. and Lowengart, A. 1998. Water and nutrient efficiency in growing bananas in subtropics. Acta Hort. 490, 117–126.

Liebenberg, A.J., 2002. Dry Bean Production. Directorate Agricultural Information Services, Department of Agriculture in cooperation with ARC-Grain Crops Institute. Department of Agriculture, Forestry and Fisheries, Republic of South Africa. http://www.nda.agric.za/docs/drybean/drybean.pdf, Electronic source, accessed on 17 December, 2015.

Lunze, L., Abang, M., Buruchara, R., Ugen, M.A., Nabahungu, N.L., Rachier, G.O., Ngongo, M., Rao, I. 2012. Integrated Soil Fertility Management in Bean-Based Cropping Systems of Eastern, Central and Southern Africa, in: Whalen, J.K.

(Ed.), Soil Fertility Improvement and Integrated Nutrient Management – A Global Perspective. InTech, pp. 239–272.

Maingi, J.M., Shisanya, C.A., Gitonga, N.M., 2001. Nitrogen fixation by common bean (*Phaseolus vulgaris* L.) in pure and mixed stands in semi-arid south-east Kenya. Eur. J. Agron. 14, 1–12.

Margaret, N., Tenywa, J.S., Otabbong, E., Mubiru, D.N., Ali, T., 2014. Development of common bean (*Phaseolus vulgaris* L.) production under low soil phosphorus and drought in Sub-Saharan Africa: A Review. J. Sustain. Dev. 7, 128–139.

Mazur, R., Tenywa, M., Miiro, R., Semalulu, O., Maria, R., Salégua, V., Abbott, E., Lenssen, A., Luvaga, E., Yost, R., Bello-Bravo, J., Pittendrigh, B., 2015. Farmer Decision Making Strategies for Improved Soil Fertility Management in Maize – Bean Production Systems, in: Legume Innovation Lab 2015 Annual Technical Progress Report. http://legumelab.msu.edu/project/s02_1_isu, Electronic source, accessed on 11 February, 2016.

Mazur, R., Tenywa, M., Sseguya, H., Semalulu, O., Maria, R., Sumila, C., Salégua, V., Abbott, E., Lenssen, A., Luvaga, E., Yost, R., Bello-Bravo, J., Pittendrigh, B., 2014. Farmer Decision Making Strategies for Improved Soil Fertility Management in Maize – Bean Production System, in: Legume Innovation Lab 2014 Annual Technical Progress Report. http://legumelab.msu.edu/project/s02_1_isu, Electronic source, accessed on 11 February, 2016.

Mazur, R., Nakimbugwe, D., Musoke, H., Vasanthakaalam, H., Kibwika, P., Bwambale, N., Westgate, M., Reddy, M., Ugen, M., Elepu, G., Jensen, H., Henrich, S., Murphy, P. 2012. Enhancing Nutritional Value and Marketability of Beans through Research and Strengthening Key Value Chain Stakeholders in Uganda and Rwanda, in: Dry Grain Pulses Collaborative Research Support Program, FY 2012 Technical Progress Reports, East Lansing, Michigan, pp. 3-40. http://legumelab.msu.edu/uploads/files/TechProgReportF12Final.pdf, Electronic source, accessed on 11 February, 2016.

Mengel, K., Kirkby, E.A., 1980. Potassium in Crop Production. Adv. Agron. 33, 59–110.

Nabhan, H., Mashali, A.M., Mermut, A.R., 1999. Integrated soil management for sustainable agriculture and food security in southern and east Africa, Integrated soil management for sustainable agriculture and food security. FAO. Rome.

Ojiem, J.O., Franke, A.C., Vanlauwe, B., de Ridder, N., Giller, K.E., 2014. Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. Field Crops Res. 168, 75-85.

Oosterhuis, D.M., Loka, D.A., Kawakami, E.M., Pettigrew, W.T., 2014. The physiology of potassium in crop production. Adv. Agron. 126, 203-333.

Page, S., Chonyera, P., 1994. The promotion of maize fertilizer packages: A cause of household insecurity and peasant impoverishment in high rainfall areas of Zimbabwe. Dev. South. Afr. 11, 301-320.

SAS Institute Inc., 2013. SAS/STAT User's Guide. Version 9.4. SAS Institute Inc., Cary, NC, USA.

Sebuwufu, G., Mazur, R., Ugen, M., Westgate, M., 2015. Using improved varieties and fertility enhancements for increasing yield of common beans (*Phaseolus vulgaris* L.) grown by small-landholder farmers in Uganda. Afr. J. Agric. Res. 10, 4795-4805.

Sinclair, T.R., Vadez, V., 2012. The future of grain legumes in cropping systems. Crop Pasture Sci. 63, 501–512.

UBOS and ICF International Inc., 2012. Uganda Demographic and Health Survey 2011, ICF International Inc. Kampala, Uganda.

Uganda Export Promotion Board, 2005. Dry Beans: Product Profile No. 12. http://s3.amazonaws.com/zanran_storage/www.ugandaexportsonline.com/ContentPages/2470693312.pdf, Electronic source, accessed on 17 December, 2015.

Ugen, M.A., Wien, H.C., Wortmann, C.S., 2002. Dry bean competitiveness with annual weeds as affected by soil nutrient availability. Weed Sci. 50, 530–535.

Ugen, M.A., Wortmann, C.S., 2001. Weed flora and soil properties in subhumid tropical Uganda. Weed Technol. 15, 535–543.

USDA, NRCS, 1999. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. 2nd ed. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf, Electronic source, accessed on 17 December, 2015.

Van Schoonhoven, A., Pastor-Corrales, M.A., 1987. Standard system for the evaluation of bean germplasm. http://pdf.usaid.gov/pdf_docs/PNABG497.pdf, Electronic source, accessed on 17 December, 2015.

Weisser, W.W., Volkl, W., Hassell, M.P., 1997. The importance of adverse weather conditions for behavior and population ecology of an aphid parasitoid. J. Anim. Ecol. 66, 386-400.

World Bank Group, 2015. Average monthly temperature and rainfall for Uganda from 1990-2012. http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=UGA, Electronic source, accessed on 17 December, 2015.

Wortmann, C.S., Kirkby, R.A., Eledu, C.A., Allen, D.J., 1998a. Atlas of common bean (*Phaseolus vulgaris* L.) production in Africa. International Center for Tropical Agriculture, Cali, Colombia. 133 p. (CIAT publication; no. 297).

Wortmann, C.S., Silver-Rwakaikara, M., Lynch, J., 1998b. Efficiency of nitrogen acquisition and utilisation in common bean in Uganda. Afr. Crop Sci. J. 6, 273–282.

Table 1

Agricultural inputs and management methods for each management system in the 2014B season and the 2015A season.[a-b]

		2014B[a]			**2015A**[a]		
Property	Units	CFS[b]	IFS[b]	HIS[b]	CFS[b]	IFS[b]	HIS[b]
Lime	kg ha^{-1}	0	295	295	0	0	0
P_20_5	kg ha^{-1}	0	34	34	0	45	45
K_2O	kg ha^{-1}	0	0	0	0	112	112
Vitavax	applied	No	No	Yes	No	No	Yes
Rhizobia	applied	No	No	Yes	No	No	Yes
Planting	seeds m^{-2}	10	20	20	10	20	20
Planting	method	Scattered	Rows	Rows	Scattered	Rows	Rows
Fungicide	g ha^{-1}	0	0	458	0	0	458
Insecticide	L ha^{-1}	0	0	2.5	0	0	2.5
Weeding[c]	frequency	Twice	Twice	Weekly	Twice	Twice	Weekly

[a] Rainy season: 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

[b] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

[c] Weeding was done by hand between plants and with a hand hoe between rows.

Table 2

Bean cultivar descriptions for two new and improved cultivars, NABE 14 and NABE 15, and two older conventional cultivars, K132 and NABE 4.[a]

Official name	**NABE 14**	**NABE 15**	**K132**	**NABE 4**
Other names	NAADS	Kanyebwa	Nambaale omuwanvu (long)	Nambaale omumpi (short)
Year of release	2006	2010	1994	1999
New/Old	New	New	Old	Old
Seed size	Large	Medium	Large	Medium-Large
Seed color	Red kidney	Tan/Pink mottled	Red mottled	Red mottled
Growth habit	Bush bean	Bush bean	Bush bean	Bush bean
Maturity (days)	85-90	60-65	80-85	85-90
Yield potential (kg ha^{-1})	1500-2000	1800-2000	1500-2000	2000-2500
Market reaction	Very good	Very good	Very good	Good
Disease tolerance	Tolerant to root rots, ALS, BCMV, and low soil fertility. Susceptible to anthracnose.	Tolerant to anthracnose, ALS, BCMV, CBB, and drought. Susceptible to root rots.	Susceptible to nearly all diseases.	Tolerance to CBB, ALS, and low soil fertility.
Altitude	Mid-high	All altitudes	Low-mid	Low-mid
Other	Long time to cook	Tasty and swells on cooking	Tasty and swells on cooking; short time to cook	Tasty and swells on cooking; short time to cook

[a] ALS, Angular Leaf Spot (*Phaeoisariopsis griseola*); BCMV, Bean Common Mosaic Virus (*Potyvirus* spp.); CBB, Common Bacterial Blight (*Xanthomonas campestris* pv. *phaseoli*).

Table 3

Monthly precipitation during the course of the study, long-term precipitation, and long-term temperature.

Month(s)	Precipitation[a] (mm)		Precipitation[a] (number of rainy days)		Precipitation[a] (LT[b]) (mm)	Temperature[d] (LT[b]) (°C)
	2014	2015	2014	2015		
January	-	3	-	2	42	23.9
February	-	34	-	4	44	24.9
March	-	108	-	8	96	24.5
April	-	364	-	17	152	24.0
May	394	298	18	15	129	23.2
June	103	50	7	4	88	22.7
July	77	-	7	-	83	22.3
August	106	-	6	-	114	22.7
September	97	-	8	-	118	22.9
October	112	-	8	-	142	23.1
November	69	-	9	-	111	23.5
December	63	-	11	-	56	23.5
March-June	-	820 [c]	-	44	465[c]	23.6
August-December	447 [c]	-	42	-	541[c]	23.1
January - December	-	-	-	-	1175	23.4

[a] Precipitation values recorded within 1km of the experimental site; located 13 km NE of Masaka, Central Region, Uganda.

[b] LT: long term (1990-2012) for Uganda (World Bank Group, 2015).

[c] Crop growing season precipitation.

[d] Mean temperature.

Table 4

Pre-amendment and post-harvest soil (0 to 15-cm depth) nutrient concentrations, CEC, EC, organic matter, and base saturation results from the three common bean management systems.[a-c]

Property	Units	Pre-amendment[b]			Post-harvest[b]		
		CFS[c]	IFS[c]	HIS[c]	CFS[c]	IFS[c]	HIS[c]
pH		6.7	6.6	6.8	6.6	6.5	6.5
CEC	meq	13	14	14	15	16	15
EC(S)	uS cm^{-1}	77	86	84	99	100	111
Extr. Al	meq	0.014 b	0.013 b	0.015 b	0.125 a	0.125 a	0.125 a
P	mg kg^{-1}	20	29	30	27	32	27
K	mg kg^{-1}	74	126	101	89	124	101
Mg	mg kg^{-1}	333 ab	311 b	360 ab	392 a	348 ab	350 ab
Ca	mg kg^{-1}	1710	1828	1850	1898	2058	1910
Na	mg kg^{-1}	40 a	55 a	51 a	11 b	45 a	27 ab
Al	mg kg^{-1}	830	846	854	-	-	-
Mn	mg kg^{-1}	340 b	335 b	354 b	467 a	460 a	473 a
S	mg kg^{-1}	3	3	2	2	3	5
Cu	mg kg^{-1}	2.9 c	3.0 c	3.0 c	4.0 b	4.4 a	4.1 b
B	mg kg^{-1}	0.5	0.5	0.5	0.7	0.9	0.7
Zn	mg kg^{-1}	5.1	5.7	5.2	6.4	6.6	6.2
Fe	mg kg^{-1}	97 b	97 b	97 b	132 a	135 a	134 a
N	%	0.11 b	0.12 b	0.12 b	0.16 a	0.16 a	0.16 a
OM	g kg^{-1}	36	37	36	38	34	36
C:N	ratio	18	18	18	14	12	13
Base Saturation	%	90	90	92	89	88	88

[a] Means within property followed by the same letter, or no letter, are not different at *P*=0.05.

[b] Soil collected from Masaka District, Uganda. Collection period: Pre-amendment, July 2014; and post-harvest, December 2014.

[c] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

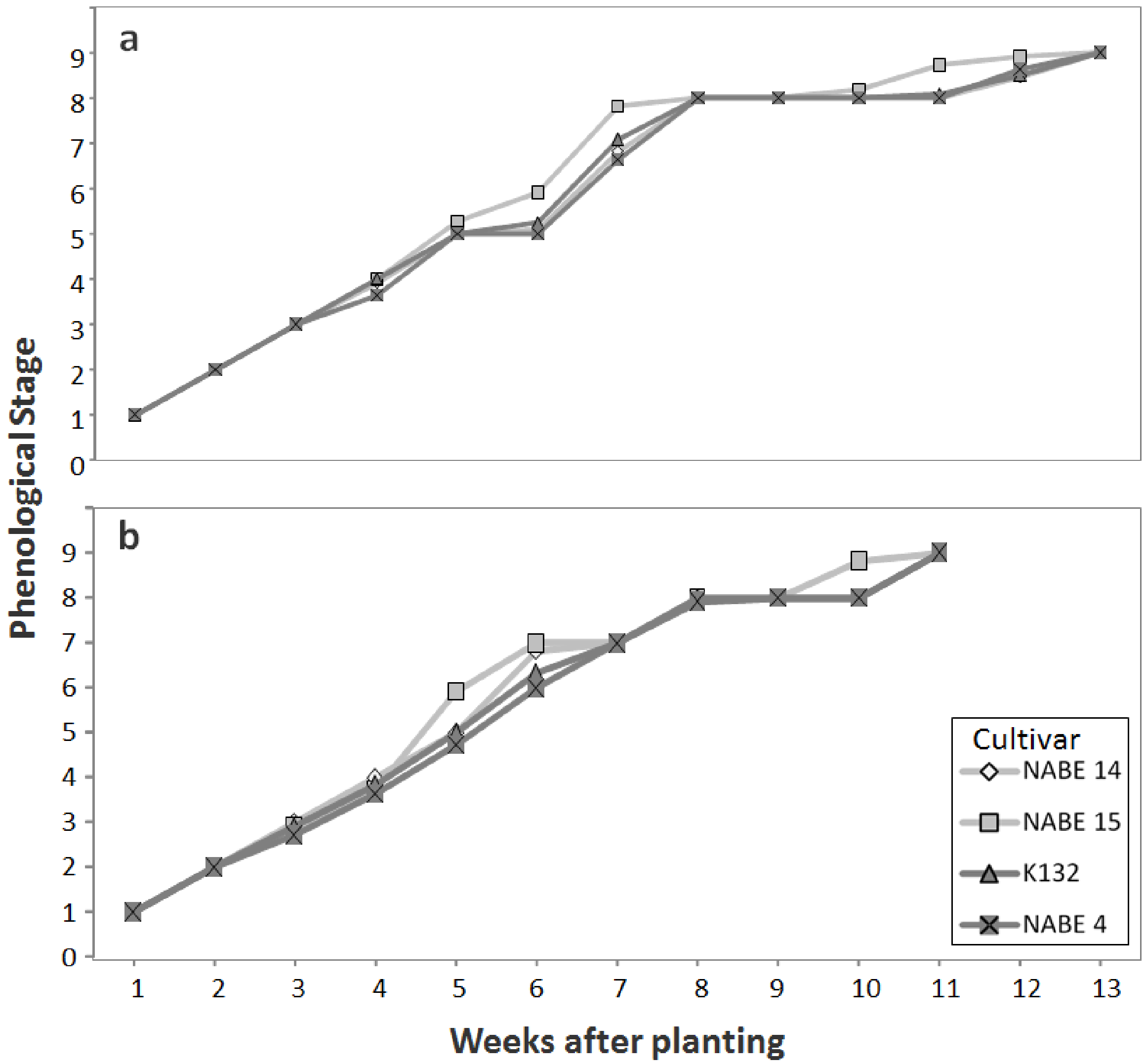

Fig. 1. Weekly mean phenological stage of bean for four cultivars in (a) the 2014B season and (b) the 2015A season across three management systems, Masaka, Uganda. 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

Table 5

Yield, yield components, height, biomass, pod harvest index (PHI), and net profit/loss for four bean cultivars in three management systems for two rainy seasons, Masaka, Uganda.[a-c]

Treatment	Plant stand (# m^{-2}) R9	Extended plant height (cm)	Pods (# m^{-2})	Seed (# pod^{-1})	Seed size (100 seed weight, g)	Biomass (g $plant^{-1}$) R8-R9	Grain (kg ha^{-1})	Pod Harvest Index (PHI)	Economic Return to Labor and Management (USD)
Management System[b]									
CFS	6 b	29	40 b	2.9	42.5	21	593 b	76	212
IFS	14 a	31	67 ab	2.8	38.7	16	818 b	77	124
HIS	16 a	34	92 a	2.9	43.7	18	1275 a	75	297
Cultivar									
NABE 14	14 a	36 a	90 a	3.2	41.7 ab	22 a	1212 a	73 b	378 a
NABE 15	10 c	23 c	52 b	2.6	37.8 b	18 ab	668 c	81 a	79 c
K132	11 b	34 ab	62 b	2.8	43.1 a	17 b	803 bc	74 ab	165 bc
NABE 4	13 a	32 b	63 b	2.9	43.9 a	16 b	899 b	76 a	220 b
Rainy season[c]									
2014B	12	38 a	91 a	3.3	44.5 a	27 a	1318 a	76	466 a
2015A	12	25 b	42 b	2.5	38.8 b	9 b	473 b	76	-44 b
Significance				*P* > F					
System (S)	***	NS	*	NS	NS	NS	*	NS	NS
Cultivar (C)	***	***	***	***	*	*	***	*	***
S × C	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rainy season (R)	NS	***	***	***	***	***	***	NS	***
S × R	NS	**	*	NS	NS	**	**	NS	***
C × R	**	**	***	***	NS	***	***	NS	***
S × C × R	NS	NS	*	NS	NS	NS	*	NS	*

[a] Means within treatment and column followed by the same letter, or no letter, are not different at *P*=0.05.*, **, ***, and NS indicate statistical significance at *P* ≤ 0.05, 0.01, 0.001, and not significant, respectively.

Table 5 continued

[b] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

[c] Rainy season: 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

Table 6

Interaction of cultivar × rainy season for R9 plant stand density, height, seed number, and aboveground biomass of bean for two seasons.[a-b]

Parameter	2014B[b]	2015A[b]
Plant stand (# m^{-2}) R9		
NABE 14	13 a	14 a
NABE 15	10 b	10 c
K132	12 a	10 c
NABE 4	13 a	13 b
Height (cm)		
NABE 14	39 a	34 a
NABE 15	32 b	15 c
K132	38 a	29 a
NABE 4	41 a	23 b
Seed (# pod^{-1})		
NABE 14	3.3 ab	3.1 a
NABE 15	3.3 ab	1.9 c
K132	3.0 b	2.6 b
NABE 4	3.5 a	2.3 b
Biomass (g $plant^{-1}$) R8-R9		
NABE 14	26	18 a
NABE 15	30	5 b
K132	26	8 b
NABE 4	27	6 b

[a] Means within parameter and rainy season followed by the same letter, or no letter, are not different at *P*=0.05.

[b] Rainy season: 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

Table 7

Interaction of management system × rainy season for height and biomass of bean for two seasons.[a-c]

Parameter	2014B [c]	2015A[c]
Height (cm)		
CFS[b]	37	22 b
IFS[b]	39	23 ab
HIS[b]	37	30 a
Biomass (g plant^{-1}) R8-R9		
CFS[b]	32 a	9
IFS[b]	25 b	7
HIS[b]	24 b	11

[a] Means within parameter and rainy season followed by the same letter, or no letter, are not different at *P*=0.05.

[b] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

[c] Rainy season: 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

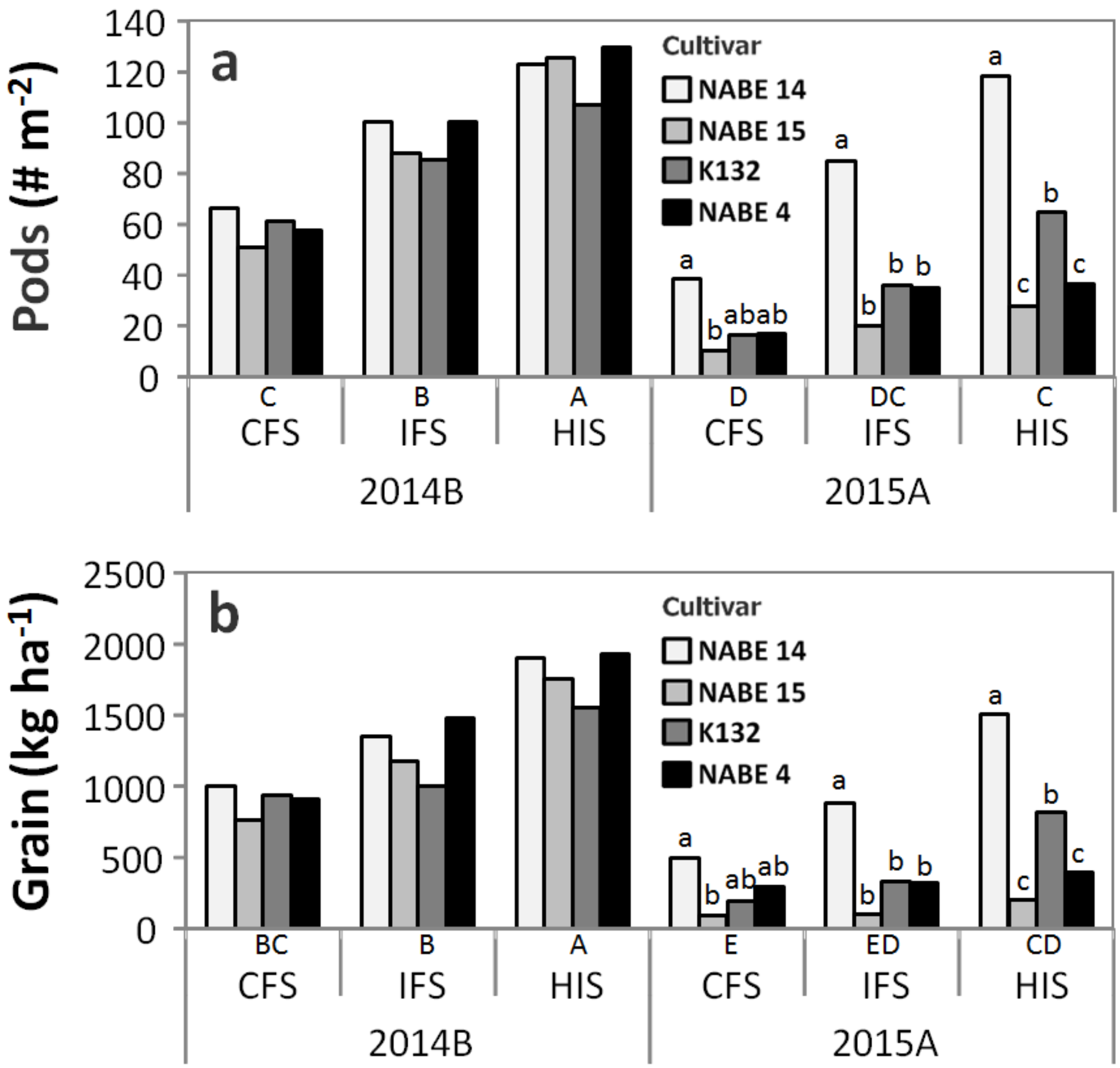

Fig. 2. Interaction of management system × cultivar × rainy season for (a) pod density and (b) grain yield of beans. Management systems include the Conventional Farmer System (CFS), Improved Farmer System (IFS), and High Input System (HIS). 2014B, 2014 second rainy season; 2015A, 2015 first rainy season. Cultivar means within system and rainy season followed by the same lowercase letter, or no letter, are not different at *P*=0.05. System × rainy season combinations followed by the same uppercase letter are not different at *P*=0.05.

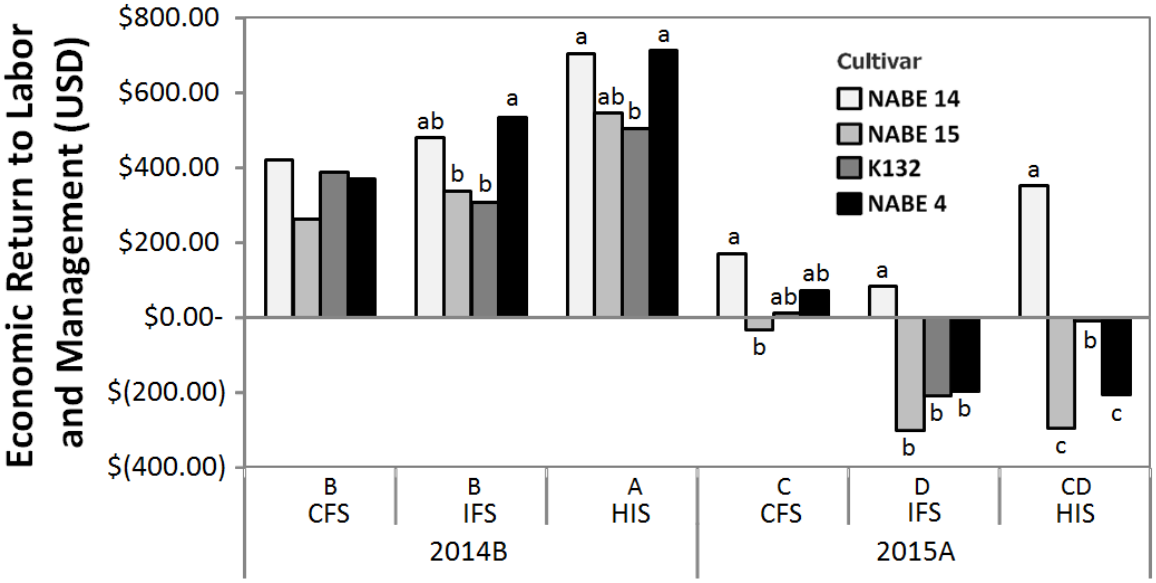

Fig. 3. Interaction of management system × cultivar × rainy season for 'return to labor and management' of beans. Management systems include the Conventional Farmer System (CFS), Improved Farmer System (IFS), and High Input System (HIS). 2014B, 2014 second rainy season; 2015A, 2015 first rainy season. Cultivar means within system and rainy season followed by the same lowercase letter, or no letter, are not different at *P*=0.05. System × rainy season combinations followed by the same uppercase letter are not different at *P*=0.05.

CHAPTER 4. IMPROVED PRODUCTION SYSTEMS FOR COMMON BEAN IN SOUTH-CENTRAL UGANDA. II. LIMYUFUMYUFU SOIL

A paper formatted for Field Crops Research

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Abstract

Common bean (*Phaseolus vulgaris* L.) is the most important source of dietary protein in Uganda but current grain yields are extremely low. Production is particularly low on the degraded Limyufumyufu soils (Ferralsols) that dominate the landscape because these soils are generally weathered, acidic, and infertile. Land in Uganda is increasingly farmed more intensively due to the greater demand for food production for the ever growing population, which has led to further soil degradation and low yields. It is therefore important to develop improved management systems to increase bean yields on this degraded soil of south-central Uganda. A study was conducted on Limyufumyufu soil in Masaka District, Uganda to compare the productivity and the economic return to labor and management (ERLM) for four bean cultivars grown under three management systems. The experiment was designed as a randomized complete block in a split-plot

arrangement. Management system was the whole-plot factor and included the Conventional Farmer (CFS), Improved Farmer (IFS), and High Input systems (HIS). Management systems differed for seed fungicide treatment (no vs. yes), seeding density (10 vs. 20 seed m^{-2}), plant configuration (scatter vs. rows), fertilizer applications (P, K, Ca, Mg, Zn, and S), rhizobium inoculation (no vs. yes), pesticide applications (no vs. yes), and frequency and timing of weeding. Subplots were four bush type common bean cultivars that differed for resistance to foliar pathogens and the ability to tolerate low soil fertility. Increasing management level and planting bean cultivars tolerant to common bean diseases and low soil fertility improved bean grain yield. There were only grain yield differences between cultivars in the 2015A season and NABE 14 had the greatest grain yield (772 kg ha^{-1}), which was 168% greater than NABE 15 (288 kg ha^{-1}). The HIS with NABE 14 (1274 kg ha^{-1}), the HIS with NABE 4 (1225 kg ha^{-1}), and the IFS with NABE 14 (1025 kg ha^{-1}) had the greatest management system × cultivar combinations for grain yield. The increased yields for these management system × cultivar combinations were likely due to the cultivars' greater host plant resistance to several bean diseases and tolerance to low soil fertility. The economic return to labor and management was only profitable for the CFS (\$40 ha^{-1}), and no differences were observed between cultivars. Additionally, across management systems and cultivars, both rainy seasons resulted in a net loss. All inputs and seed of bean cultivars used were obtained locally, except the rhizobia, suggesting that increased yields are obtainable by farmers on the Limyufumyufu soil but increased profits are not possible with the current high prices of agricultural inputs and low market price of bean.

Keywords

Food security; *Phaseolus vulgaris* L.; soil fertility; management systems; improved cultivars; sustainable intensification

Acronyms and Abbreviations

2014B – 2014 second rainy season

2015A – 2015 first rainy season

ALS – Angular leaf spot

BCMV – bean common mosaic virus

EC – electrical conductivity

ECCE – effective calcium carbonate equivalent

ERLM – economic return to labor and management

CEC – cation exchange capacity

CEDO – Community Enterprises Development Organisation

CFS – Conventional Farmer System

CIAT – International Center for Tropical Agriculture

FAO – Food and Agriculture Organization

HIS – High Input System

ICP-OES – inductively coupled plasma optical emission spectrometry

IFS – Improved Farmer System

PHI – pod harvest index

UEPB – Uganda Export Promotion Board

UGX – Ugandan shilling

UNESCO – United Nations Educational, Scientific and Cultural Organization.

USAID – United State Agency for International Development

USDA NRCS – U.S. Department of Agriculture Natural Resources Conservation Service

VWC – volumetric water content

WAP – weeks after planting

1. Introduction

Low soil fertility and acidity are the most important common bean (*Phaseolus vulgaris* L.) productivity constraints in East Africa (Lunze et al., 2007). Bean is an important crop worldwide but it is especially important in East Africa where it is a staple crop for dietary protein (Kweka, 2001). Despite its importance, bean needs more attention as an alternative to expensive livestock protein to meet the dietary needs of the ever growing population of Uganda. Uganda's population has increased very rapidly which has consequently increased the pressure on the land through continuous cultivation and reducing the frequency of traditional fallow periods (Ronner and Giller, 2012). Conventional management practices have resulted in infertile and degraded soils due to soil fertility mining (Nabhan et al., 1999).

Uganda's population is estimated to be 34.9 million (Uganda Bureau of Statistics, 2014), with 80% living in rural Uganda. Population density reaches an average of 143 persons km^{-2} in some rural regions (Ronner and Giller, 2012). Uganda is dominated by smallholder farmers and Mazur et al. (2015) recorded an average farm size of only 1.2 ha in south-central Uganda. Due to low opportunities of employment, many people are living off of subsistence agriculture and therefore desire a crop that is productive, profitable, and nutritious (Kilimo Trust, 2012); however, due to limited land, beans are often grown on highly weathered soils and are rarely productive or profitable under conventional management practices.

Beans are grown on many types of soils in Uganda but the strongly weathered soils, such as Ferralsols, form more than 70% of the soil on which most of the farming is practiced (Wortmann et al., 1998a; Bekunda et al., 2002). Beans are preferentially grown on darker, more fertile soils (Mazur et al., 2015) but due to the rising population and growing demand for an inexpensive source of protein (Kilimo Trust, 2012), nearly all of the land favorable for row crop agriculture is already in production. This leaves the highly weathered and nutrient depleted, acidic soils to be utilized for crop production (Ronner and Giller, 2012). These soils require a great amount of inputs to improve both soil chemical fertility and pH (Nabhan et al., 1999) because they are strongly leached and have lost nearly all of their weatherable minerals (Jones et al., 2013). Consequently, these soils are dominated by stable products such as aluminum oxides, iron oxides, and kaolinite, giving this soil its red color (Jones et al., 2013). These Al and Fe oxides often bind with P, making it unavailable for plant uptake. It is therefore important to lime these soils to increase the cation exchange capacity (CEC), neutralize Al, and to increase the supply of essential minerals such as Ca, K, and Mg (Lunze et al., 2012). A target pH of 5.8 to 6.5 is favorable for bean production (Lunze et al., 2012) and when the pH is in this range minerals become more soluble, microorganisms are more active, and plant nutrient uptake improves.

Unfortunately, bean production on these red soils is low and very little research has suggested methods to increase bean production on these acidic weathered soils. Due to the prevalence of highly weathered soils in south-central Uganda, management systems that alleviate the constraints to increase production and profitability are needed. Ronner and Giller (2012) showed considerable improvements in bean yield and profitability when adding fertilizer but other research suggests it may be unwise to invest in high input agriculture because the yield increases may not be enough to cover the value of the inputs (Ojiem et al., 2014; Page and Chonyera, 1994). This is especially important in low fertility and acidic soils that require substantial amounts of inputs to become productive. Currently, inorganic fertilizer is applied in very low quantities in Uganda, despite many soils being nutrient depleted (Ronner and Giller, 2012). The high cost of inorganic fertilizer limits its use and therefore may only be profitable on fertile soils, whereas poor soils are only minimally impacted by the fertilizer and therefore less profitable (Ronner and Giller, 2012).

Soil amendments are effective at improving soil productivity but smallholder farmers cannot afford the amounts required to correct soil pH and nutrient deficiencies (Lunze et al., 2007). Alternatively, bean cultivars with tolerance to edaphic stresses can make it possible to improved bean yield and profitability on these low fertility and acidic soils by reducing the farmers’ dependency on fertilizers and therefore reducing production costs (Singh et al., 2003; Lunze et al., 2007). Disease resistant cultivars have been developed to avoid the risk of yield losses but adoption is low (Broughton et al., 2003). Bekunda (2004) and Esilaba (2005) expressed the need for improved management of beans, which included the need for research on improved cultivars and soil fertility systems. To address the constraints limiting bean production on Limyufumyufu (Ferralsol) soil in south-central Uganda, we developed a study with the objective of comparing grain yield and profitability of four bean cultivars grown under a conventional and two improved management systems in order to determine which cultivar and system combination is the most productive and profitable on the weathered and acidic Limyufumyufu soil of this region.

2. Materials and Methods

2.1 Experimental site

The experimental site was located approximately 13 km northeast of Masaka, Central Region, Uganda (latitude 0^{o} 15’ 49.2552” S; longitude 31^{o} 48’ 32.8752” E; altitude 1281 m). The climate is tropical and generally rainy with two dry seasons (Jones et al., 2013). Soil at the location was called Limyufumyufu (reddish) in the local language but is defined as a Ferralsol using the FAO-UNESCO soil legend and as a Eutrudox using USDA Soil Taxonomy (FAO, 1988; USDA NRCS, 1999).The soil at the experimental site was a sandy clay loam texture and formed from alluvial deposits. Prior to adding soil amendments, soil at the 0 to 15 cm depth had a pH range of 5.2 to 5.4, Mehlich-3 P ranged from 4 to 6 mg kg^{-1}, and organic matter (OM) ranged from 41 to 43 g kg^{-1}. Long term mean annual precipitation in Uganda is 1175 mm, with about 86 percent occurring through the crop growing seasons (World Bank Group, 2015). Precipitation data for the specific research site were not available before this project. According to the landowner, prior to the initiation of this study, the site had been in a maize (*Zea mays*), bean (*Phaseolus vulgaris* L.), groundnut (*Arachis hypogaea*), banana (*Musa* spp.), and cassava (*Manihot esculenta*) intercrop.

2.2 Experimental design

The experimental design and many of the materials and methodologies used in this study were similar or identical to those reported in a related study by Goettsch (2016).

The study was initiated in July 2014 and continued over two seasons, the second rainy season of 2014 (2014B), from the end of August through the beginning of December, and the first rainy season of 2015 (2015A), from the end of March through the middle of June. The experimental design was a randomized complete block in a split-plot arrangement. Management system was the whole-plot factor and included Conventional Farmer System (CFS), Improved Farmer System (IFS), and High Input System (HIS) (Table 1). The subplots were four bush type common bean cultivars. Two cultivars were new and improved, NABE 14 and NABE 15, and two were conventional cultivars, K132 and NABE 4 (Table 2). The new cultivars were released 7 to 16 years later (2006 & 2010) than the older cultivars (1994 &1999) and have greater resistance to several bean diseases prevalent in the south-central region of Uganda. Individual subplot size measured six meters by four meters. There were four replications of each management system × cultivar subplot combination. Replications were blocked perpendicular to the slope.

2.3 Crop management practices

Perennial crops and residual weeds from the previous rainy season were removed using a hand hoe more than one month prior to planting in the 2014B season. Ground agricultural limestone with 68.85 percent effective calcium carbonate equivalent (ECCE) containing 38 percent Ca, 0.29 percent Mg, 0.10 percent S, and 1.24 percent P was applied at 15,900 kg ha^{-1} to neutralize the soil pH. Results from analysis of pre-plant soil samples showed available K was low, therefore, muriate of potash was broadcast by hand prior to tillage both seasons in the IFS and HIS. Potassium was applied at 44.8 kg ha^{-1} in the 2014B season and 112 kg ha^{-1} in the 2015A season. One to two weeks prior to planting, tillage was conducted with a hand hoe to a depth of 15-20 cm over a period of several days. Beans planted in the CFS were scatter planted at a density of 10 seeds m^{-2} while beans in the IFS and HIS were planted in rows 50 cm wide with seeds planted every 10 cm, which resulted in the recommended planting density of 20 seeds m^{-2} for both the IFS and HIS (UEPB, 2005). The 10 seeds m^{-2} rate for the CFS was determined by extensive sampling of farmer bean fields in Masaka District the previous rainy season, 2014A (Mazur et al., 2014)

Bean seeds were obtained from Community Enterprises Development Organisation (CEDO) located in Rakai, Uganda. Seed for HIS were treated with VITAVAX® (Bayer CropScience, Research Triangle Park, NC.) fungicide (carboxin: (5,6-Dihydro-2-methyl-N-phenyl-1,4-oxathiin-3-carboxamide) by CEDO personnel. Seeds planted in the IFS and HIS were inoculated with Mak-Bio-Fixer rhizobia obtained from Makerere University prior to planting. Before planting the IFS and HIS, triple superphosphate (0-46-0) was banded at 84 kg P_2O_5 ha^{-1} in the IFS and the HIS in the

2014B season and at 67.3 kg P_2O_5 ha^{-1} in both improved management systems in the 2015A season. These bands were placed in hand dug furrows at a depth of 8-10 cm and covered with 2-4 cm of soil, similar to the technique described by Lunze et al. (2012). Beans were then placed at the recommended depth of 3-5 cm (Liebenberg, 2002; Amongi et al., 2014) before being covered with soil using a hand hoe. Beans were planted 17 and 18 August during the 2014B season and 23 March for the 2015A season.

Formulated azoxystrobin (methyl (E)-2-{2[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate) was applied as a foliar fungicide at 458 g ha^{-1} to the HIS both seasons. The fungicide was applied using a hand-pumped backpack sprayer in approximately 625 L H_2O ha^{-1} at the early stages of R8 pod filling in the 2014B season and at the late stages of R7 pod formation in the 2015A season. Four days after applying the fungicide in the 2014B season, the insecticide cypermethrin ((±)α-cyano-(3-phenoxyphenyl)methyl(±)-*cis-trans*-3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate) formulated as Dudu-Cyper® 5 percent EC (Bukoola Chemical Industries LTD, Kampala, Uganda) was foliar-applied to the HIS beans at a rate of 2.5 L ha^{-1} mixed with 3.36 kg ha^{-1} of $ZnSO_4$. This mixture was applied to the HIS with the hand-pumped backpack sprayer in approximately 625 L H_2O ha^{-1}. In the 2015A season, the fungicide, insecticide, and $ZnSO_4$ were foliar-applied with the backpack sprayer as a mix to the HIS, to minimize the number of trips across the plots, at the same rates as the previous season. The IFS received the $ZnSO_4$ application both seasons at a rate of 3.36 kg ha^{-1}.

Weeding was done by hand between plants and with a hand hoe between rows twice per season for the CFS and IFS. The first weeding was done at V3 in the 2014B season and between V3 and V4 in the 2015A season. The second weeding occurred between R7 and R8 both seasons. Weeding was done weekly for the HIS, using the same method, so that weeds were never competitive with beans.

2.4 Crop and soil data collection

The pre-amendment and post-harvest soil samples were collected at a depth of 0 to 15 cm from 12 subsamples collected from each replication of each whole-plot. Soil samples were analyzed for pH and electrical conductivity (EC) using the potentiometric method. Extractable aluminum, percent organic matter, and percent N were determined by colorimetry. The CEC was calculated according to the same methods published in The Nature and Properties of Soils (Brady and Weil, 2007). After extraction with Mehlich-3 ICP-OES, the soil samples were analyzed for P, K, Mg, Ca, Na, Al, Mn, S, Cu, B, Zn, and Fe; the C:N ratio was calculated.

Phenological development stages were recorded weekly in each plot using the standard system developed for common bean (Fernandez et al., 1986; Van Schoonhoven and Pastor-Corrales, 1987). Between R8 and R9, aboveground crop biomass was determined by hand clipping five bean plants per plot. Bean biomass samples were placed into labelled bags for transport to Makerere University for oven drying. Biomass samples were oven-dried at 60˚C for 7 days and then weighed. The yield, yield components, and extended plant height data were collected from all bean plants within the area harvested from each plot. The area harvested in the CFS was selected by randomly placing two 1.0 m^2 quadrats in each plot (2.0 m^2 total). The IFS and HIS yield samples were determined from two 2-meters of row in each plot (2.0 m^2 total). Stand density of bean at the R9 stage was determined at harvest by counting the number of plants within each harvested area. Extended plant height was measured on every plant harvested, up to a maximum of ten plants per subplot. At harvest, all pods were hand-picked, counted, placed in a paper bag, and brought to a scale to be weighed. Pods were taken to Makerere University where they were placed in an oven at 60˚C until dry. Seed were then shelled from pods by hand, counted, and weighed. The pod harvest index (PHI; dry weight of seed at harvest/dry weight of pod at harvest × 100), pod number per area (pods m^{-2}), and seed number per pod (seeds pod^{-1}) were computed as described by Beebe et al. (2013). Reported grain yields represent oven-dried weight.

Soil volumetric water content (VWC) was determined using a FIELDSCOUT® TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Plainfield, IL). Sampling occurred weekly in each subplot at two points for each of the two depths, 7.5 and 20 cm.

The costs of production and market prices of beans were determined using local market prices for all of the agricultural inputs, except rhizobia, which was unavailable in the local market. Rhizobia inoculant was available at Makerere University; it was assumed inoculation will occur every four seasons. Labor costs were reported using a combination of data collected from this study's labor costs, labor costs collected from the Farmer Decision Making Strategies for Improved Soil Fertility Management in Maize-Bean Production Systems project (Mazur et al., 2014, 2015), and a report from the Uganda Export Promotion Board (2005), which provided a representative cost for labor in this region. The market price of bean used in this analysis assumed beans were sold immediately after harvest when farm gate prices ranged from 1500 to 1700 UGX kg^{-1}, depending on the bean cultivar. The UGX to USD conversion rate used for this study was 3400 UGX = 1 USD.

2.5 Statistical analysis

Data were analyzed as a randomized complete block in a split-plot arrangement with management system as the whole-plot factor and bean cultivar as the subplot factor. Statistical analyses for yield, yield components, height, biomass, PHI, VWC, phenological, and economic data were performed with the GLIMMIX Procedure of SAS V9.4 (SAS Institute, 2013). Least squares means were generated for all variables when significant F values ($P < 0.05$) were observed and then separated using the LINES option at $P = 0.05$. Soil data were analyzed using PROC GLM, which enabled us to separate means using the multiple mean comparison of the protected least significant difference. Differences among treatments were reported as significant at $P = 0.05$ except for the phenological differences between treatments, which were reported as significant at $P = 0.01$. Management system, cultivar, rainy season, and weeks after planting (WAP) were treated as fixed effects. Replication, replication × management system, and cultivar × replication × management system were considered random effects for analyses of crop, soil, and economic data.

3. Results

3.1 Climate

Climate results are identical to those reported in a related study by Goettsch (2016) (Table 3). Long-term mean annual precipitation for this region is 1175 mm, 86% of which occurs during the crop growing season (World Bank Group, 2015). Total precipitation during our study, July 2014 through June 2015, was 1381 mm, 18% greater than the long-term normal. Precipitation during the dry season months, July and again January through February, amounted to only 67% of the 22-yr average for these months. However, the precipitation in April 2015 was 139% greater than that of the long-term average and the precipitation in May 2015 was 131% greater than that of the long-term average. Mean long term monthly air temperature ranged from a low of 22.3^{o}C in July to a high of 24.9^{o}C in February (World Bank Group, 2015). Temperature data were not collected at our research site during the period of this study.

3.2 Soil

The pre-amendment soil results differed among management systems for Cu and Zn; all other physico-chemical parameters measured were similar among management systems (Table 4). Conversely, there were greater levels of the following properties in the two improved management systems in the post-harvest soil data compared to the pre-amendment soil data: pH, CEC, EC(S), P, K, Ca, S, B, Cu, Zn, Fe, N, and base saturation percentage (Table 4). Additionally, post-harvest soil results differed for management systems for pH, CEC, EC(S), P, K, Ca, Na, Cu, Zn, and base saturation percentage.

3.3 Volumetric water content

The VWC differed for management system, rainy season, and the interaction of rainy season × depth. All other main effects and interactions were not significant. The VWC differed for depth both rainy seasons. The mean VWC in the 2014B season was 0.19 cm^3 cm^{-3} and 0.21 cm^3 cm^{-3} for 7.5 cm depth and 20 cm depth, respectively while mean VWC in the 2015A season was 0.26 cm^3 cm^{-3} and 0.24 cm^3 cm^{-3} for 7.5 cm depth and 20 cm depth, respectively. The 2014B season was wetter at 20 cm depth compared to 7.5 cm depth while the reverse was true for the 2015A season.

3.4 Phenological growth stages

The phenological development of beans varied for all main effects and their interactions, except management system (results not presented). The interaction of cultivar × rainy season × WAP was significant (Fig. 1). In both seasons there was a divergence of cultivars with NABE 15 reaching stage five of development sooner than other entries. However, in subsequent WAP, cultivars were once again at similar development stages. Then around 10 WAP, both seasons, NABE 15 diverged for a week before converging at maturation (R9). In the 2014B season, maturity was reached in 13 weeks while in the 2015A season maturity was reached in just 11 weeks (Fig. 1).

3.5 Yield, yield components, height, biomass, and pod harvest index (PHI)

At maturity (R9 stage), stand density of beans differed for management system, cultivar, rainy season, and interactions of management system × cultivar and cultivar ×

rainy season (Table 5). In both rainy seasons NABE 15 had the lowest stand density (Table 6). Differences were observed in stand density each rainy season × management system, which is due to the differences in planting density. Plant stands did not differ between rainy seasons for the IFS or HIS but there was a decrease in plant stand for the CFS. The CFS resulted in eight plants m^{-2} in the 2014B season but only four plants m^{-2} in the 2015A season (results not presented).

Height of beans at harvest varied for management system, cultivar, rainy season, and the interaction of cultivar × rainy season (Table 5). In both rainy seasons, bean cultivars differed in height (Table 6). NABE 4 was taller than NABE 15 and NABE 14 in the 2014B season while K132 was the tallest and NABE 15 was the shortest in the 2015A season.

Pod density of beans differed for management system, cultivar, rainy season, and the interaction of cultivar × rainy season (Table 5). NABE 14 produced the fewest pods m^{-2} in the 2014B season and NABE 15 produced the fewest pods m^{-2} in the 2015A season (Table 6).

Seed number pod^{-1} varied for management system, cultivar, rainy season, and the interactions of management system × cultivar, management system × rainy season, and cultivar × rainy season (Table 5). Seed number pod^{-1} varied for cultivar in the HIS but cultivar did not vary for CFS or IFS (Table 7). NABE 14 had the greatest seeds pod^{-1} in the HIS. In both rainy seasons, seed number pod^{-1} varied for cultivar (Table 6). NABE 14 frequently produced more seeds pod^{-1} than the other cultivars while K132 produced among the fewest seeds pod^{-1} both seasons. Seeds pod^{-1} varied for management system only in the 2015A season (Table 8). The IFS and HIS produced more seeds pod^{-1} than the CFS in the 2015A season.

The 100-seed weight varied for management system and rainy season; however, the interactions were not significant (Table 5). Cultivar did not influence 100-seed weight but the seed weight in the 2014B season was 28% greater than for the 2015A season. K132 produced the heaviest seed, weighing 12% greater than NABE 14.

Aboveground biomass (g plant^{-1}) varied for rainy season and the three-way interaction of management system × cultivar × rainy season (Table 5). Biomass samples were not taken from nine CFS plots and one IFS plot in the 2015A season because plant stands were low. Collecting these plants for aboveground biomass would have compromised our ability to harvest grain yield and grain yield components. Consequently, we were unable to calculate protected least significant difference tests when including the 2015A season. Excluding the 2015A season and looking only at the 2014B season, aboveground biomass did not vary for any main effect or interaction.

Grain yield differed for management system, cultivar, rainy season, and the interactions of management system × cultivar and cultivar × rainy season (Table 5). Grain yield differed for cultivar in the HIS but cultivar did not influence yield in the CFS or IFS (Table 7). Under the HIS, NABE 14 (1274 kg ha^{-1}) and NABE 4 (1225 kg ha^{-1}) produced the greatest grain yields. Cultivars only varied for grain yield in the 2015A season (Table 6). NABE 14 produced the greatest grain yield (772 kg ha^{-1}) in the 2015A season, recording 168% greater yield than NABE 15 (288 kg ha^{-1}).

The PHI varied for management system, cultivar, rainy season, and the interaction of management system × rainy season; all other treatment factors and interactions were not significant (Table 5). The PHI only varied for management system in the 2015A season when the IFS and HIS had 16 and 25% greater PHI than CFS (Table 8).

3.6 Economic analysis

Management system and rainy season influenced the economic return to labor and management (ERLM) but the other main effects and interactions did not influence net profit or loss (Table 5). The ERLM in the 2014B season was greater than for the 2015A season; however, both seasons resulted in a net loss. The CFS produced the only profitable ERLM as IFS and the HIS only produced net losses. Cultivar did not influence ERLM.

4. Discussion

4.1 Climate, volumetric water content, and phenological growth stages

Due to the close proximity of this research on Limyufumyufu (Ferralsol) soil and the research on Liddugavu (Phaeozem) soil, weather data were collected at one location and was previously reported by Goettsch (2016). Precipitation was favorable for bean production during the 2014B season but the increased frequency and amount of rain in the 2015A season was unfavorable for bean production, and likely was a primary factor for decreased yields and increased VWC in the 7.5 cm depth compared to the 20 cm depth in the 2015A season. The VWC results were nearly identical to the results reported for our Liddugavu results (Goettsch, 2016), which may be due to the close proximity of these two locations and their similarities in soil texture. The differences in phenological development between cultivars at each date most likely were due to genetic differences in maturity among the four cultivars; this was also observed in our related study (Goettsch, 2016). Interestingly, NABE 15 reached a few developmental stages quicker than others cultivars which would suggest that this cultivar had more leaves sooner and therefore a potential for greater yields due to increased capture of light energy; however, this particular cultivar requires fewer days to reach maturity compared to the other three cultivars and therefore reached a few developmental stage sooner.

4.2 Pests and diseases

We expected to see lower yields in the 2015A season compared to the 2014B season because beans were planted on the same plots as the previous season. The bean-bean rotation could have been the cause for the greater occurrence of disease in the 2015A season; however, it could have also been due to the increased VWC in the soils, which is conducive to root rots and other diseases (Athanase et al., 2013). The increased amount of rain in the 2015A season compared to the 2014B season could have caused the decreased prevalence of aphids (Weisser et al., 1997). Foliar diseases were less prevalent on the NABE 14 and NABE 4 cultivars both seasons, which is likely due to their tolerance to foliar diseases. Surprisingly, NABE 15 had many disease symptoms even though it was selected to have tolerance to many common diseases (Table 2).

4.3 Cultivar selection and management of agricultural inputs and soil nutrients

Farmers prefer to plant bean on black soils (Liddugavu) because they know that reddish soils (Limyufumyufu) are less fertile and a poorer growing environment for bean production (Mazur et al., 2014). Even though the Limyufumyufu soil is considered infertile, these soils rarely receive a fertilizer application, perhaps due to the greater amounts needed to increase production. Furthermore, it is questionable on whether or not a return on investment is possible due to the great amount of expensive agricultural inputs required for increased production and the low market price of beans received at the farm gate. In most regions, beans are planted in rotation with cereals and therefore only benefit from the residual fertilizer applied in the previous season (Lunze et al., 2012).

We replanted beans on the same plots both seasons to develop a better understanding of lime carry-over effects on pH within each management system. The lime application increased pH to a level above the target range of 5.8 to 6.5 because lime requirement functions were not developed before this project began. Lime requirements have since been developed for several soils in south-central Uganda by Tenywa et al. (personal communication, 2016). The main concern we had with agricultural lime was its cost and the great amount needed to reach the target pH range. We had similar economic concerns with the amount and cost of fertilizer needed. A compliment, or perhaps an alternative, to agricultural lime and fertilizer would be the adoption of improved cultivars with tolerance to low soil fertility, low soil pH, and soluble Al. New cultivars with tolerance to low soil pH and soluble Al have been developed by Beebe et al. (personal communication, 2015) at CIAT and are a promising alternative to costly lime applications. However, it is unknown when adapted cultivars with tolerance to low soil pH will be available for smallholder farmers in rural villages. As stated by Lunze et al. (2007), the fast option to soil fertility management is the genetic approach, e.g. tolerant bean cultivars. Additionally, it is unknown whether soil acid-tolerant beans will have the characteristics Ugandan consumers prefer when choosing cultivars, including taste, market prices, and cooking time (Mazur et al., 2012; Kilimo Trust, 2012).

A few bean cultivars have been documented to perform well under edaphic stresses; therefore, for comparison purposes, we chose two cultivars that are tolerant to low soil fertility and two that are not. When choosing the four cultivars we ensured that each of them was accessible by smallholder farmers before we tested for productivity under infertile soil and high acidity conditions. The variability in performance between these cultivars was interesting and the reason for the greatest grain yield from NABE 14 is likely due to the combined differences in maturity, adaptation to low soil fertility, and resistance to common fungal diseases compared to the other cultivars. The tolerance to edaphic stress and multiple disease resistance in NABE 14 makes it a superior cultivar that could improve yield for Ugandan bean farmers planting on red soil.

4.4 Economic analysis

Ferralsols are widely reported as infertile (Fungo et al., 2011; Musinguzi et al., 2015) with low productivity potential for bean (Nabhan et al., 1999), especially compared to the Liddugavu soil described by Goettsch (2016). The Liddugavu soil had more favorable pH, CEC, and better level of macronutrients and micronutrients compared to the Limyufumyufu soil. The greater level of infertility and need for higher rates of nutrients for enhanced bean production on Limyufumyufu resulted in poor yields and poor economic returns to labor and management. Ojiem et al. (2014) also stated that soils with greater levels of infertility yielded less and consequently provided smaller economic returns. This is in agreement with Ronner and Giller (2012), who stated that it was profitable to fertilize fertile soils but fertilizing poor soils had only limited impact on yield and therefore limited profitability. The need for inputs was too great and the value of bean was too low to recover the investment for nearly all of our management system × cultivar × rainy season combinations.

5. Conclusions

Lime and fertilizer prices need to be lower for high input bean production systems to become profitable on the Limyufumyufu soils of south-central Uganda. The development of management systems that limit the use of expensive agricultural inputs and utilize improved cultivars with a tolerance to low soil fertility and acidity is necessary to improve bean yield. This would likely increase food security, decrease production costs, and generate greater income. The only combination that was profitable on this Limyufumyufu soil in our study was the CFS in the 2014B season. This suggests, if growing beans on this soil type, it is currently only appropriate to recommend growing beans during rainy season B and to minimize the use of expensive agricultural inputs if the goal is to recover the greatest return on investment.

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References

Amongi, W., Nkalubo, S.T., Ochwo-Ssemakula, M., Gibson, P., Edema, R., 2014. Development of intermittent drought stress tolerant common bean genotypes in Uganda. Afr. Crop Sci. J. 22, 303–315.

Athanase, C., Tenywa, J.S., Tenywa M.M., Okiror, J.J., Leonidas, D., Mupenzi, M., Augustine, M., 2013. Farmers' Coping Mechanisms for Common Bean Production under Water-Logged Soil Conditions in Uganda-Rwanda Boarder Region. J. Environ. Sci. Eng. B. 2, 46-52.

Beebe, S.E., Rao, I.M., Blair, M.W., Acosta-Gallegos, J.A., 2013. Phenotyping common beans for adaptation to drought. Front. Physiol. 4, 1–21.

Bekunda, M.A., Nkonya, E., Mugendi, D., Msaky, J.J., 2002. Soil fertility status, management, and research in East Africa. East Afr. J. Rural Dev. 20, 94–112.

Brady, N.C., Weil, R.R., 2007. The colloidal fraction: seat of soil chemical and physical activity, in: The Nature and Properties of Soils, 14th ed. Prentice Hall, pp. 310–357.

Broughton, W.J., Hernández, G., Blair, M., Beebe, S., Gepts, P., Vanderleyden, J., 2003. Beans (*Phaseolus* spp.) – model food legumes. Plant Soil 252, 55–128.

Esilaba, A.O., Nyende, P., Nalukenge, G., Byalebeka, J.B., Delve, R.J., Ssali, H., 2005. Resource flows and nutrient balances for crop and animal production in smallholder farming systems in eastern Uganda. Agric. Ecosyst. Environ. 109, 192–201.

FAO, 1988. FAO/UNESCO Soil Map of the World. Revised Legend, with corrections and updates.

Fernandez, F., Gepts, P., Lopez, M., 1986. Stages of development of the common bean plant; study guide to be used as a supplement to the audio tutorial unit on the same topic. CIAT. Cali, Colombia. 32p. (Series 04EB-09.03).

Fungo, B., Grunwald, S., Tenywa, M., Vanlauwe, B., Nkedi-Kizza, P., 2011. Lunnyu soils in the Lake Victoria basin of Uganda: Link to toposequence and soil type. Afr. J. Environ. Sci. Technol. 5, 15–24.

Goettsch, L., 2016. Improved production systems for common bean in south-central Uganda. I. Liddugavu soil. (Master's thesis), Iowa State University, Ames, Iowa.

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M., Zougmoré R., (eds.), 2013. Soil Atlas of Africa. European Commission, Publications Office of the European Union, Luxembourg. 176 pp.

Kilimo Trust, 2012. Development of Inclusive Markets in Agriculture and Trade (DIMAT): The Nature and Markets of Bean Value Chains in Uganda. http://www.undp.org/content/dam/uganda/docs/UNDP%20Uganda_PovRed%20-%20Beans%20Value%20Chain%20Report%202013.pdf, Electronic source, accessed on 17 December, 2015.

Kweka, S.O., Ndakidemi, P.A., Mushi, C.S., Nkonya, E., and David, S. 2001. Adoption of Lyamungu 85 bean variety in the medium-altitude zone of Tanzania. Pan-African Bean Research Network (PABRA) Millennium Workshop, 28 May-1 June, Arusha, Tanzania, CIAT, Kampala, pp. 147–151.

Liebenberg, A.J., 2002. Dry Bean Production. Directorate Agricultural Information Services, Department of Agriculture in cooperation with ARC-Grain Crops Institute. Department of Agriculture, Forestry and Fisheries, Republic of South Africa.http://www.nda.agric.za/docs/drybean/drybean.pdf, Electronic source, accessed on 17 December, 2015.

Lunze, L., Abang, M., Buruchara, R., Ugen, M.A., Nabahungu, N.L., Rachier, G.O., Ngongo, M., Rao, I. 2012. Integrated Soil Fertility Management in Bean-Based Cropping Systems of Eastern, Central and Southern Africa, in: Whalen, J.K. (Ed.), Soil Fertility Improvement and Integrated Nutrient Management – A Global Perspective. InTech, pp. 239–272.

Lunze, L., Kimani, P.M., Ngatoluwa, R., Rabary, B., Rachier, G.O., Ugen, M.M., Ruganza V., Awad elkarim E.E., 2007. Bean improvement for low soil fertility in adaptation in Eastern and Central Africa. In: Bationo, A., Waswa, B., Kihara, J. & Kimetu J. (Eds.) Advances in integrated soil fertility management in sub-Saharan

Africa: Challenges and Opportunities, pp. 325 – 332. Springer, Dordrecht, The Netherlands.

Mazur, R., Tenywa, M., Miiro, R., Semalulu, O., Maria, R., Salégua, V., Abbott, E., Lenssen, A., Luvaga, E., Yost, R., Bello-Bravo, J., Pittendrigh, B., 2015. Farmer Decision Making Strategies for Improved Soil Fertility Management in Maize – Bean Production Systems, in: Legume Innovation Lab 2015 Annual Technical Progress Report. http://legumelab.msu.edu/project/s02_1_isu, Electronic source, accessed on 11 February, 2016.

Mazur, R., Tenywa, M., Sseguya, H., Semalulu, O., Maria, R., Sumila, C., Salégua, V., Abbott, E., Lenssen, A., Luvaga, E., Yost, R., Bello-Bravo, J., Pittendrigh, B., 2014. Farmer Decision Making Strategies for Improved Soil Fertility Management in Maize – Bean Production System, in: Legume Innovation Lab 2014 Annual Technical Progress Report. http://legumelab.msu.edu/project/s02_1_isu, Electronic source, accessed on 11 February, 2016.

Mazur, R., Nakimbugwe, D., Musoke, H., Vasanthakaalam, H., Kibwika, P., Bwambale, N., Westgate, M., Reddy, M., Ugen, M., Elepu, G., Jensen, H., Henrich, S., Murphy, P. 2012. Enhancing Nutritional Value and Marketability of Beans through Research and Strengthening Key Value Chain Stakeholders in Uganda and Rwanda, in: Dry Grain Pulses Collaborative Research Support Program, FY 2012 Technical Progress Reports, East Lansing, Michigan, pp. 3-40. http://legumelab.msu.edu/uploads/files/TechProgReportF12Final.pdf, Electronic source, accessed on 11 February, 2016.

Musinguzi, P., Tenywa, J.S., Ebanyat, P., Basamba, T.A., Tenywa, M.M., Mubiru, D.N., Zinn, Y.L., 2015. Soil organic fractions in cultivated and uncultivated Ferralsols in Uganda. Geoderma Regional. 4, 108–113.

Nabhan, H., Mashali, A.M., Mermut, A.R., 1999. Integrated soil management for sustainable agriculture and food security in southern and east Africa, Integrated soil management for sustainable agriculture and food security. FAO. Rome.

Ojiem, J.O., Franke, A.C., Vanlauwe, B., de Ridder, N., Giller, K.E., 2014. Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. Field Crops Res. 168, 75-85.

Page, S., Chonyera, P., 1994. The promotion of maize fertilizer packages: A cause of household insecurity and peasant impoverishment in high rainfall areas of Zimbabwe. Dev. South. Afr. 11, 301-320.

Ronner, E., Giller, K., 2012. Background information on agronomy, farming systems and ongoing projects on grain legumes in Uganda, pp 1-34. https://www.n2africa.org/sites/n2africa.org/files/images/N2Africa_Characterization%20Uganda.pdf, Electronic source, accessed on 27 January 2016.

SAS Institute Inc., 2013. SAS/STAT User's Guide. Version 9.4. SAS Institute Inc., Cary, NC, USA.

Singh, S.P., Teran, H., Munoz, C.G., Osorno, J.M., Takegami, J.C., Thung, M.D.T., 2003. Low soil fertility in landraces and improved common bean genotypes. Crop Sci. 43, 110–119.

Singh, S.P., 2001. Broadening the genetic base of common bean cultivars: a review. Crop Sci. 41, 1659–1675.

Uganda Bureau of Statistics, 2014. National Population and housing Census 2014. Provisional results, 1–65. http://www.ubos.org/onlinefiles/uploads/ubos/NPHC/NPHC%202014%20PROVISIONAL%20RESULTS%20REPORT.pdf, Electronic source, accessed on 17 December, 2015.

Uganda Export Promotion Board (UEPB), 2005. Dry Beans: Product Profile No. 12. http://s3.amazonaws.com/zanran_storage/www.ugandaexportsonline.com/ContentPages/2470693312.pdf, Electronic source, accessed on 17 December, 2015.

USDA, NRCS, 1999. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. 2nd ed. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf, Electronic source, accessed on 17 December, 2015.

Van Schoonhoven, A., Pastor-Corrales, M.A., 1987. Standard system for the evaluation of bean germplasm. http://pdf.usaid.gov/pdf_docs/PNABG497.pdf, Electronic source, accessed on 17 December, 2015.

Weisser, W.W., Volkl, W., Hassell, M.P., 1997. The importance of adverse weather conditions for behavior and population ecology of an aphid parasitoid. J. Anim. Ecol. 66, 386-400.

World Bank Group, 2015. Average monthly temperature and rainfall for Uganda from 1990-2012. http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=UGA, Electronic source, accessed on 17 December, 2015.

Wortmann, C.S., Kirkby, R.A., Eledu, C.A., Allen, D.J., 1998. Atlas of common bean (*Phaseolus vulgaris* L.) production in Africa. International Center for Tropical Agriculture, Cali, Colombia. 133 p. (CIAT publication; no. 297).

Table 1

Agricultural inputs and management methods for each management system in the 2014B season and the 2015A season.[a-b]

		2014B [a]			2015A [a]		
Property	Units	CFS [b]	IFS [b]	HIS [b]	CFS [b]	IFS [b]	HIS [b]
Lime	kg ha^{-1}	0	15,900	15,900	0	0	0
P_20_5	kg ha^{-1}	0	84	84	0	67	67
K_2O	kg ha^{-1}	0	45	45	0	112	112
$ZnSO_4$	kg ha^{-1}	0	3.4	3.4	0	3.4	3.4
Vitavax	applied	No	No	Yes	No	No	Yes
Rhizobia	applied	No	Yes	Yes	No	Yes	Yes
Planting	seeds m^{-2}	10	20	20	10	20	20
Planting	method	Scattered	Rows	Rows	Scattered	Rows	Rows
Fungicide	g ha^{-1}	0	0	458	0	0	458
Insecticide	L ha^{-1}	0	0	2.5	0	0	2.5
Weeding	frequency	Twice	Twice	Weekly	Twice	Twice	Weekly

[a] Rainy season: 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

[b] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

[c] Weeding was done by hand between plants and with a hand hoe between rows.

Table 2

Bean cultivar descriptions for two new and improved cultivars, NABE 14 and NABE 15, and two older conventional cultivars, K132 and NABE 4.[a]

Official name	**NABE 14**	**NABE 15**	**K132**	**NABE 4**
Other names	NAADS	Kanyebwa	Nambaale omuwanvu (long)	Nambaale omumpi (short)
Year of release	2006	2010	1994	1999
New/Old	New	New	Old	Old
Seed size	Large	Medium	Large	Medium-Large
Seed color	Red kidney	Tan/Pink mottled	Red mottled	Red mottled
Growth habit	Bush bean	Bush bean	Bush bean	Bush bean
Maturity (days)	85-90	60-65	80-85	85-90
Yield potential (kg ha^{-1})	1500-2000	1800-2000	1500-2000	2000-2500
Market reaction	Very good	Very good	Very good	Good
Disease tolerance	Tolerant to root rots, ALS, BCMV, and low soil fertility. Susceptible to anthracnose.	Tolerant to anthracnose, ALS, BCMV, CBB, and drought. Susceptible to root rots.	Susceptible to nearly all diseases.	Tolerance to CBB, ALS, and low soil fertility.
Altitude	Mid-high	All altitudes	Low-mid	Low-mid
Other	Long time to cook	Tasty and swells on cooking	Tasty and swells on cooking; short time to cook	Tasty and swells on cooking; short time to cook

[a] ALS, Angular Leaf Spot (*Phaeoisariopsis griseola*); BCMV, Bean Common Mosaic Virus (*Potyvirus* spp.); CBB, Common Bacterial Blight (*Xanthomonas campestris* pv. *phaseoli*).

Table 3

Monthly precipitation during the course of the study, long-term precipitation, and long-term temperature.

Month(s)	Precipitation[a] (mm)		Precipitation[a] (number of rainy days)		Precipitation[a] (LT[b]) (mm)	Temperature[d] (LT[b]) (°C)
	2014	2015	2014	2015		
January	-	3	-	2	42	23.9
February	-	34	-	4	44	24.9
March	-	108	-	8	96	24.5
April	-	364	-	17	152	24.0
May	394	298	18	15	129	23.2
June	103	50	7	4	88	22.7
July	77	-	7	-	83	22.3
August	106	-	6	-	114	22.7
September	97	-	8	-	118	22.9
October	112	-	8	-	142	23.1
November	69	-	9	-	111	23.5
December	63	-	11	-	56	23.5
March-June	-	820 [c]	-	44	465[c]	23.6
August-December	447 [c]	-	42	-	541[c]	23.1
January - December	-	-	-	-	1175	23.4

[a] Precipitation values recorded within 1km of the experimental site; located 13 km NE of Masaka, Central Region, Uganda.

[b] LT: long term (1990-2012) for Uganda (World Bank Group, 2015).

[c] Crop growing season precipitation.

[d] Mean temperature.

Table 4

Pre-amendment and post-harvest soil (0 to 15-cm depth) nutrient concentrations, CEC, EC, organic matter, and base saturation results from the three common bean management systems.[a-c]

Property	Units	**Pre-amendment** [b]			**Post-harvest** [b]		
		CFS [c]	IFS [c]	HIS [c]	CFS [c]	IFS [c]	HIS [c]
pH		5.2 b	5.4 b	5.4 b	5.2 b	7.0 a	7.1 a
CEC	meq	10 b	12 b	11 b	11 b	20 a	22 a
EC(S)	uS cm^{-1}	88 b	100 b	98 b	78 b	166 a	177 a
Extr. Al	meq	0.273	0.174	0.166	0.425	0.150	0.125
P	mg kg^{-1}	4 b	6 b	4 b	4 b	15 a	19 a
K	mg kg^{-1}	55 b	56 b	47 b	49 b	79 a	87 a
Mg	mg kg^{-1}	200	253	246	195	256	267
Ca	mg kg^{-1}	710 b	926 b	911 b	785 b	3138 a	3603 a
Na	mg kg^{-1}	46 ab	58 a	48 ab	25 c	30 bc	60 a
Al	mg kg^{-1}	1228	1183	1180	-	-	-
Mn	mg kg^{-1}	163 c	201 abc	182 bc	221 ab	233 a	215 ab
S	mg kg^{-1}	6 b	6 b	6 b	9 ab	12 a	13 a
Cu	mg kg^{-1}	2.0 d	2.3 c	2.2 cd	2.9 b	3.2 a	3.1 ab
B	mg kg^{-1}	0.1 c	0.2 bc	0.2 bc	0.3 ab	0.4 a	0.4 a
Zn	mg kg^{-1}	1.0 c	1.5 b	1.2 bc	1.2 bc	3.1 a	3.3 a
Fe	mg kg^{-1}	99 b	110 b	99 b	129 a	132 a	131 a
N	%	0.13 b	0.13 b	0.13 b	0.17 a	0.19 a	0.19 a
OM	g kg^{-1}	41 ab	41 ab	43 a	38 c	37 c	39 bc
C:N	ratio	18 a	18 a	18 a	13 b	12 b	12 b
Base Saturation	%	55 b	61 b	61 b	54 b	94 a	95 a

[a] Means within property followed by the same letter, or no letter, are not different at *P*=0.05.

[b] Soil collected from Masaka District, Uganda. Collection period: Pre-amendment, July 2014; and post-harvest, December 2014.

[c] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

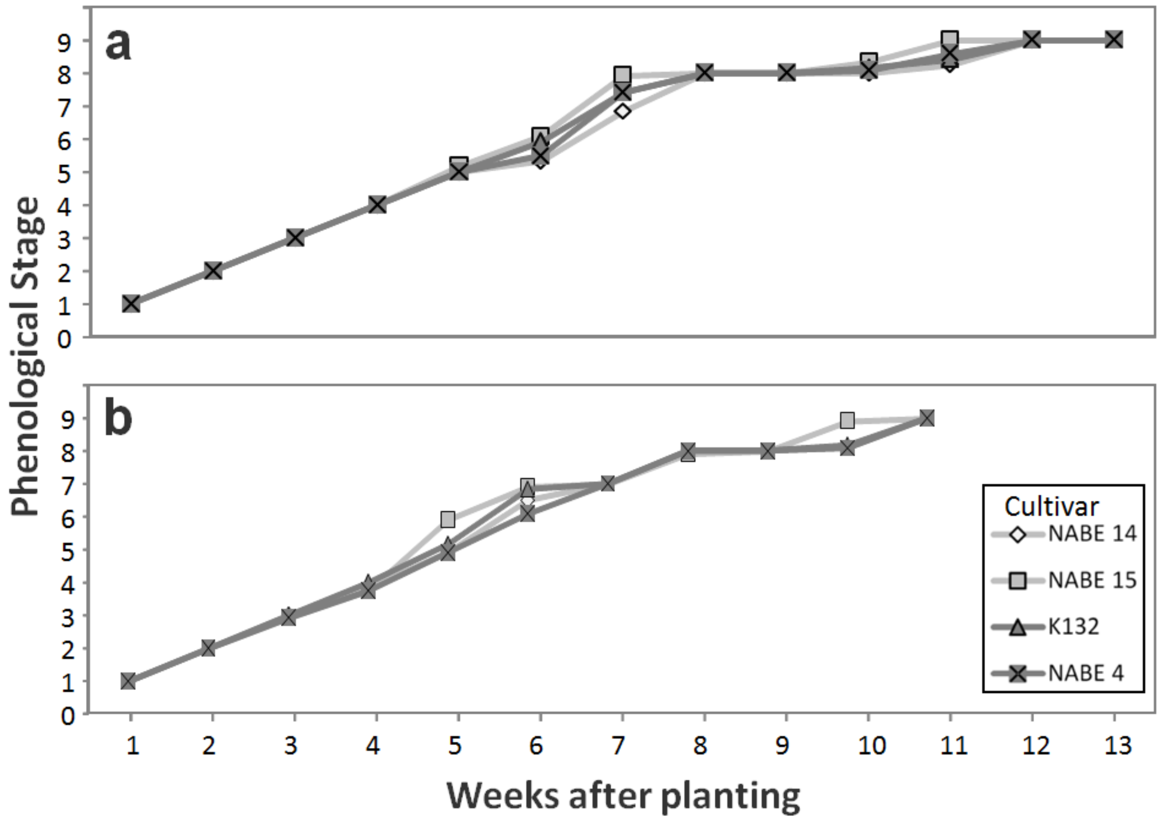

Fig. 1. Weekly mean phenological stage of bean for four cultivars in (a) the 2014B season and (b) the 2015A season across three management systems, Masaka, Uganda. 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

Table 5

Yield, yield components, height, biomass, pod harvest index (PHI), and net profit/loss for four bean cultivars in three management systems for two rainy seasons, Masaka, Uganda.[a]

Treatment	Plant stand (# m^{-2}) R9	Extended plant height (cm)	Pods (# m^{-2})	Seed (# pod^{-1})	Seed size (100 seed weight, g)	Biomass (g $plant^{-1}$) R8-R9 †	Grain (kg ha^{-1})	Pod Harvest Index (PHI)	Economic Return to Labor and Management (USD)
Management System [b]									
CFS	6 b	22 b	23 b	2.6 b	30.9 c	N/A	235 b	67 b	40 a
IFS	17 a	33 a	81 a	3.0 a	37.0 b	15	933 a	74 a	-812 b
HIS	16 a	34 a	83 a	3.1 a	41.1 a	15	1061 a	76 a	-1057 c
Cultivar									
NABE 14	14 a	29 b	62 ab	3.3 a	34.8 b	14	831 a	69 b	-583
NABE 15	11 b	23 c	54 b	2.7 b	35.9 ab	N/A	613 b	72 a	-659
K132	13 a	35 a	65 a	2.7 b	38.9 a	13	746 ab	73 a	-605
NABE 4	14 a	32 a	68 a	2.9 b	35.8 ab	13	784 a	75 a	-592
Rainy season [c]									
2014B	14 a	31 a	73 a	3.1 a	40.8 a	17	948 a	75 a	-491 a
2015A	12 b	28 b	52 b	2.7 b	31.9 b	N/A	539 b	69 b	-728 b
Significance				P > F					
System (S)	***	***	***	*	**	NS	***	*	***
Cultivar (C)	***	***	*	***	NS	NS	*	**	NS
S × C	NS	NS	NS	*	NS	NS	*	NS	NS
Rainy season (R)	***	*	***	***	***	***	***	***	***
S × R	***	NS	NS	**	NS	NS	NS	***	NS
C × R	**	***	**	*	NS	NS	***	NS	NS
S × C × R	NS	NS	NS	NS	NS	*	NS	NS	NS

[a] Means within treatment and column followed by the same letter, or no letter, are not different at P=0.05.*, **, ***, and NS indicate statistical significance at $P \leq 0.05$, 0.01, 0.001, and not significant, respectively.

Table 5 continued

[b] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

[c] Rainy season: 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

† Protected least significant difference tests were not calculated on biomass (g plant^{-1}) data because there weren't enough samples available to be collected in the 2015A season.

Table 6

Interaction of cultivar × rainy season for R9 plant stand density, height, pod density, seed number, and grain yield of bean for two seasons.[a]

Parameter	2014B [b]	2015A [b]
Plant stand (# m^{-2}) R9		
NABE 14	14 a	13 a
NABE 15	12 b	10 c
K132	15 a	12 b
NABE 4	14 a	13 a
Height (cm)		
NABE 14	30 b	28 b
NABE 15	28 b	18 c
K132	32 ab	39 a
NABE 4	35 a	29 b
Pods (# m^{-2})		
NABE 14	64 b	61 a
NABE 15	74 ab	34 b
K132	72 ab	58 a
NABE 4	81 a	56 a
Seed (# pod^{-1})		
NABE 14	3.3 a	3.3 a
NABE 15	3.0 ab	2.3 b
K132	2.9 b	2.5 b
NABE 4	3.3 a	2.5 b
Grain (kg ha^{-1})		
NABE 14	889	772 a
NABE 15	937	288 c
K132	911	582 b
NABE 4	1054	514 b

[a] Means within parameter and rainy season followed by the same letter, or no letter, are not different at *P*=0.05.

[b] Rainy season: 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

Table 7

Interaction of management system × cultivar for seed number and grain yield of bean over two seasons.[a]

Parameter	CFS [b]	IFS [b]	HIS [b]
Seed (# pod^{-1})			
NABE 14	2.8	3.3	3.9 a
NABE 15	2.3	3.0	2.7 b
K132	2.6	2.8	2.7 b
NABE 4	2.8	2.9	2.9 b
Grain (kg ha^{-1})			
NABE 14	193	1025	1274 a
NABE 15	202	865	771 b
K132	261	1003	975 b
NABE 4	286	841	1225 a

[a] Means within management system followed by the same letter, or no letter, are not different at *P*=0.05.

[b] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

Table 8

Interaction of management system × rainy season for seed number and PHI of bean for two seasons.[a]

Parameter	2014B [c]	2015A [c]
Seed (# pod^{-1})		
CFS [b]	3.1	2.1 b
IFS [b]	3.1	2.9 a
HIS [b]	3.1	3.0 a
PHI		
CFS [b]	73	61 b
IFS [b]	76	71 a
HIS [b]	77	76 a

[a] Means within parameter and rainy season followed by the same letter, or no letter, are not different at *P*=0.05.

[b] CFS, Conventional Farmer System; IFS, Improved Farmer System; HIS, High Input System.

[c] Rainy season: 2014B, 2014 second rainy season; 2015A, 2015 first rainy season.

APPENDIX A

BLACK SOIL ENTERPRISE BUDGET

	Conventional Farmer System				Improved Farmer System				High Input System			
Cultivar	NABE14	NABE15	K132	NABE4	NABE14	NABE15	K132	NABE4	NABE14	NABE15	K132	NABE4
Inputs (UGX/ha/season)												
Lime (every 6 seasons)	0	0	0	0	58,980	58,980	58,980	58,980	58,980	58,980	58,980	58,980
Seeds	156,762	134,568	165,654	162,720	313,524	269,136	331,308	325,440	353,276	290,521	422,037	355,971
Rhizobia (every 4 seasons)	0	0	0	0	0	0	0	0	8,675	8,675	8,675	8,675
Fertilizers	0	0	0	0	457,641	457,641	457,641	457,641	457,641	457,641	457,641	457,641
Pesticides	0	0	0	0	0	0	0	0	116,029	116,029	116,029	116,029
Land rent	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197
Total cost of inputs (UGX/ha/season)	**267,959**	**245,765**	**276,851**	**273,917**	**941,342**	**896,954**	**959,126**	**953,258**	**1,105,798**	**1,043,043**	**1,174,559**	**1,108,493**
Yield – grain (kg/ha)	746	425	561	602	1,117	639	663	897	1,706	982	1,187	1,161
Unit cost of production (UGX/kg)	359	578	493	455	843	1,404	1,447	1,063	648	1,062	990	955
Most probable farm gate price (UGX/kg)	1,700	1,500	1,700	1,700	1,700	1,500	1,700	1,700	1,700	1,500	1,700	1,700
C: Profitability (UGX/ha)												
Gross value of output	1,268,200	637,500	953,700	1,023,400	1,898,900	958,500	1,127,100	1,524,900	2,900,200	1,473,000	2,017,900	1,973,700
Net income (UGX/ha)	1,000,241	391,735	676,849	749,483	957,558	61,546	167,974	571,642	1,794,402	429,957	843,341	865,207
Net income (USD/ha) (1 USD=3400 UGX)	$294.19	$115.22	$199.07	$220.44	$281.63	$18.10	$49.40	$168.13	$527.77	$126.46	$248.04	$254.47
Output:input ratio	4.73	2.59	3.44	3.74	2.02	1.07	1.18	1.60	2.62	1.41	1.72	1.78

APPENDIX B

RED SOIL ENTERPRISE BUDGET

	Conventional Farmer System				Improved Farmer System				High Input System			
Cultivar	NABE14	NABE15	K132	NABE4	NABE14	NABE15	K132	NABE4	NABE14	NABE15	K132	NABE4
Inputs (UGX/ha/season)												
Lime (every 6 seasons)	0	0	0	0	3,180,400	3,180,400	3,180,400	3,180,400	3,180,400	3,180,400	3,180,400	3,180,400
Seeds	156,762	134,568	165,654	162,720	313,524	269,136	331,308	325,440	353,276	290,521	422,037	355,971
Rhizobia (every 4 seasons)	0	0	0	0	8,675	8,675	8,675	8,675	8,675	8,675	8,675	8,675
Fertilizers	0	0	0	0	744,402	744,402	744,402	744,402	1,494,402	1,494,402	1,494,402	1,494,402
Pesticides	0	0	0	0	0	0	0	0	134,779	134,779	134,779	134,779
Land rent	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197	111,197
Total cost of inputs (UGX/ha/season)	**267,959**	**245,765**	**276,851**	**273,917**	**4,358,198**	**4,313,810**	**4,375,982**	**4,370,114**	**5,282,729**	**5,219,974**	**5,351,490**	**5,285,424**
Yield – grain (kg/ha)	193	201	261	286	1,025	865	1,003	841	1,274	771	975	1,225
Unit cost of production (UGX/kg)	1,388	1,223	1,061	958	4,252	4,987	4,363	5,196	4,147	6,770	5,489	4,315
Most probable farm gate price (UGX/kg)	1,700	1,500	1,700	1,700	1,700	1,500	1,700	1,700	1,700	1,500	1,700	1,700
C: Profitability (UGX/ha)												
Gross value of output	328,100	301,500	443,700	486,200	1,742,500	1,297,500	1,705,100	1,429,700	2,165,800	1,156,500	1,657,500	2,082,500
Net income (UGX/ha)	60,141	55,735	166,849	212,283	(2,615,698)	(3,016,310)	(2,670,882)	(2,940,414)	(3,116,929)	(4,063,474)	(3,693,990)	(3,202,924)
Net income (USD/ha) (1 USD=3400 UGX)	$17.69	$16.39	$49.07	$62.44	($769.32)	($887.15)	($785.55)	($864.83)	($916.74)	($1,195.14)	($1,086.47)	($942.04)
Output:input ratio	1.22	1.23	1.60	1.77	0.40	0.30	0.39	0.33	0.41	0.22	0.31	0.39